NON-CONVENTIONAL ENERGY SOURCES

A PROJECT SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology
in
Electrical Engineering

By

NAVAL SINGH

Department of Electrical Engineering
National Institute of Technology
Rourkela

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Under the guidance of

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CERTIFICATE OF AUTHENTICITY

This is to certify that the project report titled "Non Conventional Energy Sources" submitted by Naval Singh, Roll No. 10502067, in fulfillment of the requirements for the final year B. Tech. project in Electrical Engineering Department of National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

Date:

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About the Author

Naval Singh is a Final Year Electrical Engineering student at National Institute of Technology, Rourkela located at Orissa, an eastern state of India.

When not inside the power electronics laboratory, Naval enjoys spending time with his books, newspaper and Lenovo Y500 laptop. Naval also draws sketches and paints landscapes (though seldom simultaneously) and gets into games of badminton and cricket whenever possible.

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CONTENTS

ABSTRACT

While fossil fuels will be the main fuels for thermal power, there is fear that they will get exhausted eventually in this century. Therefore other systems based on non-conventional and renewable sources are being tried by many countries. These are solar, wind, sea, geothermal and biomass. After making a detailed preliminary analysis of biomass energy, geothermal energy, ocean thermal energy, tidal energy and wind energy, I focused mainly on Wind power for 7^{th} semester. In wind power, I have studied mechanical design of various types of wind turbines, their merits, demerits and applications, isolated and grid-connected wind energy systems with special attention to power quality. In the end I wrote, compiled and successfully executed a MATLAB program to assess the impact of a wind farm on the power system.

Solar radiation represents the earth's most abundant energy source. This energy resource has a number of characteristics that make it a very desirable option for utilization. The perennial source of solar energy provides unlimited supply, has no negative impact on the environment, is distributed everywhere, and is available freely. In India, the annual solar radiation is about 5 kWh/m^2 per day; with about 2300-3200 sunshine hours per year.

Solar energy can be exploited for meeting the ever-increasing requirement of energy in our country. Its suitability for decentralized applications and its environment-friendly nature make it an attractive option to supplement the energy supply from other sources. In 8^{th} Semester, I have made an attempt to study the ways through which solar energy can be harnessed and stored. I have also written MATLAB program to evaluate performance of fuel cell.

List of figures

List of tables

Chapter 1

Wind Energy

Wind energy

Introduction:

In the continuous search of clean, safe and renewable energy sources, wind power has emerged as one of the most attractive solutions.

Major factors that have accelerated the wind-power technology development are as follows:

1. high-strength fiber composites for constructing large low-cost blades.
2. falling prices of the power electronics.
3. variable-speed operation of electrical generators to capture maximum energy.
4. improved plant operation, pushing the availability up to 95 percent.
5. economy of scale, as the turbines and plants are getting larger in size.
6. accumulated field experience (the learning curve effect) improving the capacity factor.

India has 9 million square kilometers land area with a population over 1 billion, of which 75 percent live in agrarian rural areas. The total power generating capacity has grown from 1,300 MW in 1950 to about 100,000 MW in 1998 at an annual growth rate of about nine percent. At this rate, India needs to add 10,000 MW capacity every year. The electricity network reaches over 500,000 villages and powers 11 million agricultural water-pumping stations. Coal is the primary source of energy. However, coal mines are concentrated in certain areas, and transporting coal to other parts of the country is not easy. One-third of the total electricity is used in the rural areas, where three-fourths of the population lives. The transmission and distribution loss in the electrical network is relatively high at 25 percent. The environment in a heavilypopulated area is more of a concern in India than in other countries. For these reasons, the distributed power system, such as wind plants near the load centers, are of great interest to the state-owned electricity boards. The country has adopted aggressive plans for developing these renewables. As a result, India today has the largest growth rate of the wind capacity and is one of the largest producers of wind energy in the world.

In 1995, it had 565 MW of wind capacity, and some 1,800 MW additional capacity is in various stages of planning. The government has identified 77 sites for economically feasible wind-power generation, with a generating capacity of 4,000 MW of grid-quality power. It is estimated that India has about 20,000 MW of wind power potential, out of which 1,000 MW has been installed as of 1997. With this, India now ranks in the first five countries in the world in wind-power generation, and provides attractive incentives to local and foreign investors. The Tata Energy Research Institute's office in Washington, D.C., provides a link between the investors in India and in the U.S.A.

Classification of wind power plants:

Sl. No.	Rating (kW)	Classification
1	0.5 to 1	Very small
2	1 to 15	Small
3	15 to 200	Medium
4	250 to 1000	Large
5	1000 to 6000	Very large

Wind Farms:

1. Wind farms are the areas of land which are mainly used for developing wind power. They have 5 to 50 units.

2. These areas have continuous steady wind speed range of 6 m/s to 30m/s. Annual average wind speed of 10m/s is considered very suitable.

Wind Energy Density:

Power density of wind is proportional to cube of velocity, i.e. $\mathbf{P_w = k.\ v^3 = 0.6386.\ v^3}$

If A is the swept area of a wind turbine, then $\mathbf{P = P_w\ A}$

Energy in wind:

Energy is time integral of power.

Energy in ‘n’ hours is given by $\mathbf{E} = \int_0^n \boldsymbol{P.dh}$ (Watt-hour)

Area under P-h curve of the wind turbine gives the energy output of the wind turbine.

Efficiency Factor of wind turbine:

Efficiency of the wind turbine is given by the ratio $\boldsymbol{\eta} = \frac{\textbf{Energy output by turbine}}{\textbf{Energy in the wind}} = \frac{\boldsymbol{Po}}{\boldsymbol{Pi}}$

Power in a wind stream:

A wind stream has total power given by $\mathbf{P_t = m. (K.E._w)}$

$$= \frac{1}{2}\mathbf{m.V_i^2} \text{ (Watt)} \qquad \textbf{(1)}$$

where m = mass flow rate of air, kg/s

V_i = incoming wind velocity, m/s

Air mass flow rate is given by

$$\mathbf{m = \rho\ A\ V_i} \qquad \textbf{(2)}$$

where ρ = Density of incoming wind, kg/m^2 = 1.226 kg/m^2 at 1 atm., 15 ^{0}C

A = Cross-sectional area of wind stream, m^2

Substituting the value of 'm' from **(2)** into **(1)**, we get

$$\mathbf{P_t = \frac{1}{2}\ \rho\ A\ V_i^3} \qquad \textbf{(3)}$$

Thus, total power of a wind stream is directly proportional to

1. Density of air , ρ
2. Area of stream, A
3. Cube of velocity, V_i^3

Hence the blades of rotor should be long so that the swept area $\mathbf{A = \pi\ D^2/4}$ is large.

Efficiency of a practical propeller type wind turbine:

The maximum efficiency of a propeller type wind turbine is 59%.

Actual efficiency $\boldsymbol{\eta_a} = \mathbf{(0.5 \text{ to } 0.7)}\ \boldsymbol{\eta_{max}} = \mathbf{0.6 \times 59 = 35.4\%}$

Effect of height on the wind velocity:

In flat, open areas away from cities and forests, the wind speed increases with approximately one seventh power of the height from ground:

$$\mathbf{V = H^{1/7}}$$

This relation is valid for the heights between 50m and 250m.

Wind velocity duration curve:

This curve is drawn with number of hours of wind duration per year on X-axis to wind velocity on Y-axis.

Wind power duration curve:

This characteristic shows “number of hours per year of wind power duration” on X-axis versus “corresponding wind power” on Y-axis.

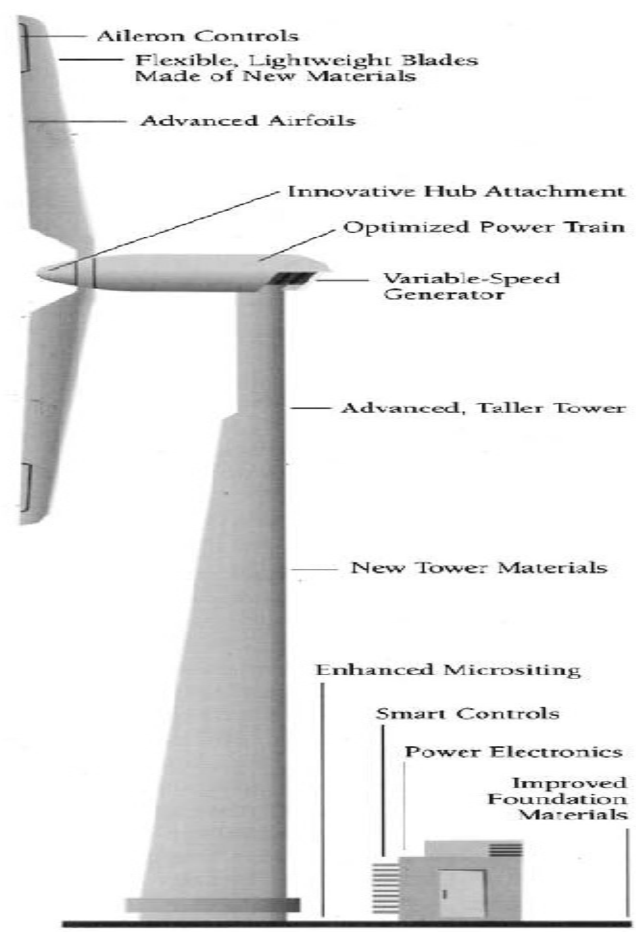
Definition of various wind speed for turbines:

1. Cut-in speed: It is speed at which wind turbine starts delivering shaft power.
2. Mean wind speed: $\mathbf{V_m} = \frac{V1+V2+V3+V4.....+Vn}{n}$

3. Rated wind speed: It is the velocity of wind at which the generator produces rated power output.
4. Cut-out wind velocity (Furling velocity): At high velocities during storms, it is necessary to cut out the power conversion of wind turbine. The speed at which power conversion is cut out is called cut-out wind velocity.

Wind turbine:

Wind turbine is a machine which converts wind power into rotary mechanical power. It has aerofoil blades mounted on rotor.



An artist's concept of a next-generation utility wind turbine is shown here.

Figure 1: A wind turbine

Wind Turbine Generator units:

A wind turbine generator consists of the following major units:

1. Wind turbine with Horizontal or Vertical axis.
2. Gear chain
3. Electrical generator (Synchronous or Asynchronous generator)
4. Civil, electrical and mechanical auxiliaries, control panels etc.

Mono-Blade Horizontal Axis Wind Turbine (HAWT):

Features:

1. They have lighter rotor and are cheaper.
2. Blade are 15-25 m long and are made up of metal, glass reinforced plastics, laminated wood, composite carbon fiber/ fiberglass etc.
3. Power generation is within the range 15 kW to 50 kW and service life of plant is 30 years.

Advantages:

1. Simple and lighter construction.
2. Favorable price
3. Easy to install and maintain.

Disadvantages:

1. Tethering control necessary for higher loads.

2. Not suitable for higher power ratings.

Applications:

1. Field irrigation
2. Sea-Water desalination Plants
3. Electric power supply for farms and remote loads.

Twin-Blade HAWT:

1. They have large sizes and power output in range of 1 MW, 2 MW and 3MW.
2. These high power units feed directly to the distribution network.

3-Blade HAWT:

1. 3 blade propeller type wind turbines have been installed in India as well as abroad.
2. The rotor has three blades assembled on a hub. The blade tips have a pitch control of $0 – 30^{0}$ for controlling shaft speed.
3. The shaft is mounted on bearings.
4. The gear chain changes the speed from turbine shaft to generator shaft.

Disadvantages of large HAWT units:

1. Complexity in design involving mechanical, metallurgical & aerodynamic.
2. Extremely high stresses during storms.
3. Installation and repair of large units is difficult.

4. Outage affects the power supply to the consumer adversely.

Persian Windmill:

1. The Persian windmill was the earliest windmill installed. (7^{th} Century A.D. – 13^{th} Century A.D. in Persia, Afghanistan and China)
2. It is a vertical axis windmill.
3. This windmill was used to grind grains and make flour.

Savonius Rotor:

1. Patented by S.J. Savonius in 1929.
2. It is used to measure wind current.
3. Efficiency is 31%.
4. It is omni-directional and is therefore useful for places where wind changes direction frequently.

Darrieus Rotor VAWT:

1. It consists of 2 or 3 convex blades with airfoil cross-section.
2. The blades are mounted symmetrically on a vertical shaft.
3. To control speed of rotation mechanical brakes are incorporated. Those brakes consist of steel discs and spring applied air released calipers for each disc.

Wind energy systems:

Based on utilization aspect:

1. Wind electric energy systems connected to grid (without need for energy storage facility).
2. Stand-Alone (Isolated) wind energy systems (with need for energy storage facility).
3. Non-critical wind electric or wind mechanical energy systems (without storage).
4. Wind Electric + Diesel Electric Hybrid or Wind Electric + Solar Electric + Battery hybrid

Based on wind turbine rotor and electrical output:

1. Constant speed constant frequency system
2. Variable speed constant frequency system
3. Nearly constant speed and constant frequency system

Constant speed constant frequency system:

1. Here, shafts of generators are coupled to output shaft of wind turbine. As wind speed is variable, therefore variable pitch blade control and gears are required to maintain constant torque output.
2. Constant frequency systems are essential for modern wind farms as the output is either grid connected or delivered to consumers requiring constant frequency supply.
3. Large WTGs use this method.

Variable Speed Constant Frequency System:

1. Thyristor convertors are used.
2. Due to variable wind speed, the generator produces variable frequency output.

3. Rectifier-inverter combination delivers constant frequency electrical output to load or grid.
4. Here, there is no need to regulate blade speed. So, turbine operates at maximum efficiency.
5. Demerit is the additional expense on controls and rectifier-inverter systems.

Nearly constant speed and constant frequency of grid:

1. Small and medium generator units rated 100 kW, 200 kW and 300 kW etc. belong to this category.
2. They use induction generators and are connected to grid.
3. Excitation current is received from grid. So, induction generator cannot be operated alone.
4. Power factor correction capacitors are also necessary.

Control and monitoring system of a wind farm:

1. A complete wind farm is controlled from the control room located in the main sub-station.
2. (X-1, X-2, X-3 …) represent control cables between individual WTG units and the master wind turbine controller.
3. The variables like power, voltage, power factor, frequency, rotor speed, pitch angle, bearing temperature, vibrations, wind direction, wind speed etc. are measured. They are converted to equivalent digital signals and transmitted via (X-1, X-2 ...) to the master controller.
4. The control has 3 levels:
   i) Distribution Network Control Centre
   ii) Master Wind Farm Controller
   iii) Unit WTG Controller
5. Signals are transmitted by radio signal system.

6. Station controller sets the power level according to instructions from the Central Distribution Control Centre.

<u>Success Stories:</u>

<u>Muppandal–Perungudi (Tamil Nadu)</u>

With an aggregate wind power capacity of 450 MW, the Muppandal–Perungudi region near Kanyakumari in Tamil Nadu has the distinction of having one of the largest clusters of wind turbines. About Rs 2500 crores has been invested in wind power in this region.

<u>Kavdya Donger, Supa (Maharashtra)</u>

A wind farm project has been developed at Kavdya Donger at Supa, off the Pune–Ahmednagar highway, about 100 km from Pune. This wind farm has 57 machines of 1-MW capacity each. Annual capacity utilization of up to 22% has been reported from this site. The farm is connected through V-SAT to project developers as well as promoters for online performance monitoring.

<u>Satara district (Maharashtra)</u>

Encouraging policy for private investment in wind power projects has resulted in significant wind power development in Maharashtra, particularly in the Satara district. Wind power capacity of about 340 MW has been established at Vankusawade, Thosegarh, and Chalkewadi in Satara district, with an investment of about Rs 1500 crores.

Wind power quality

Power quality is term used to describe how closely the electrical power delivered to customers corresponds to the appropriate standards so that the equipments of consumers operate satisfactorily. [Dugan, McGranaghan and Beaty, 1996]

Origin of power quality issues:

1. As load on the generator is removed, wind turbines over-speed. This leads to a high demand for reactive power which further depresses the network voltage.
2. Network voltage unbalance also affects the rotating induction generators by increasing losses and introducing torque ripple.
3. Voltage unbalance can also cause power converters to inject unexpected harmonics currents back into the network.
4. During normal operation, effective rotor resistance to negative sequence currents is very small $R_r/2$. So, fault current magnitude is very large.

Electrical behavior of Wind Turbine Generators:

Research conducted by [Heier, 1998], [Fiss, Weck and Weinel, 1993] gives us following inequality constraints:

For voltage change: $\sum S_{WKA}(\frac{1}{S_{KE}} - \frac{1}{S_{KSS}}) \leq \frac{1}{33}$

For voltage fluctuation: $\sqrt{\sum(\frac{P_{WKA}}{S_{KE}})^2} \leq \frac{1}{25}$

For light flicker: $\sqrt{\sum(\frac{P_{WKA}\,P_{ST}}{S_{KE}})^2} \leq \frac{1}{25}$

Here, S_{WKA} = Wind power generator apparent power

P_{WKA} = Wind power generator real power

P_{ST} = Short term flicker severity

S_{KE} = Short-circuit level at tie-line

S_{KSS} = Short-circuit level at transformer station bus-bar.

Voltage flicker:

1. It describes dynamic variations in the network voltage caused by wind turbines or varying loads. [Bossanyi, Saad-Saoud and Jenkins, 1998]
2. The origin of term is the effect of the voltage fluctuations on the brightness of incandescent lights and the subsequent annoyance of customers. [Mirra, 1998]
3. Eye is most sensitive to voltage variations around frequency of 10 Hz.
4. Power output, P and network flicker(when subject to random torque change) are related as follows:

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{n}} \frac{\Delta p}{p}$$

Here n = No. of generators

P, p = Rated power of wind farm and turbine

$\Delta P, \Delta p$ = Rated power fluctuation of wind farm and wind turbine respectively.

Harmonics:

1. Thyristors are applied to connect the induction generators to grid. As the firing angle changes, harmonics are introduced.
2. Therefore anti-parallel Thyristors need to be by-passed during normal operation.
3. Use of IGBTs significantly reduces harmonics of lower order because they operate at kHz range. High frequency harmonics can be easily filtered.
4. One disadvantage of using IGBTs is that frequencies of kHz range affect the coupling reactance X_C. This causes disturbance in the line models of distribution systems.

Comparison of voltage profile of an area before and after the introduction of a Wind energy plant

(A MATLAB® BASED APPROACH)

Problem Statement:

Output of wind farm is not at constant voltage. Also depending on the operating conditions the induction generators installed at wind farms absorb or deliver reactive power. This causes unbalance in the grid to which the wind power plant is connected.

Write a program in MATLAB to compare the effect of voltage profile of an area before and after the introduction of a Wind energy plant.

Approach:

1. Based on Gauss-Seidel method, a load flow study was formulated.
2. Individual bus admittance values were used to form admittance matrix.
3. Bus 1 was taken as slack bus.
4. Buses 2 & 3 were load buses.
5. Bus 4 was a generator bus connected to a wind farm.
6. Wind farm is an area where a large number of wind mills are installed.
7. The wind farm was considered to have 1000 wind mills.

8. Active power output depended on cube of velocity.
9. Since velocity is a stochastic variable, I limited its value within lower and upper bound to perform analysis. The velocity bounds were obtained from past analysis of weather data of the region and were 8 m/s to 20 m/s. Random velocity was generated within the bounds using rand() function.

Program:

```
clc;
clear all;
close all;
i=sqrt(-1);
 for a=1:4
    for b=1:4
        if(a~=b)
            disp(a);
            disp(b);
            disp('Enter corresponding value of y=G+iB');
            G(a,b)=input('Enter the value of G:');
            B(a,b)=input('Enter the value of B:');
            y(a,b)=G(a,b)+i*B(a,b);
```

```
        end
    end
end
 % Initialising the Y matrix to zero
for a=1:4
    for b=1:4
        Y(a,b)=0;
    end
end


% % Calculation of Y matrix
for a=1:4
    for b=1:4
        if(a~=b)
            Y(a,b)=-y(a,b);
        else
            for k=1:4
                Y(a,b)=Y(a,b)+y(a,k);
```

```
            end
        end
    end
    Y(a,b)=Y(a,b)-y(a,a);
 end
% Y=[3.0000-12.0000i -2.0000+8.0000i -1.0000+4.0000i 0;-2.0000+8.0000i 3.6660-14.6640i -
0.6660+2.6640i -1.0000+4.0000i;-1.0000+4.0000i -0.6660+2.6640i 3.6660-14.6640i -2.0000+8.0000i;0 -
1.0000+4.0000i -2.0000+8.0000i 3.0000-12.0000i];
for a=1:4
   disp('BUS NO. :');
   disp(a);
   bval(a)=input('Press 0 if slack bus,1 if PV bus or 2 if PQ bus : ');
   if(bval(a)~=0)
      P(a)=input('Enter the value of P:');
      if(bval(a)==1)
         P(a)=(0.05-0.0033)*rand;
      end
      if(bval(a)~=1)
```

```
        Q(a)=input('Enter the value of Q:');
      end
   end
   if(bval(a)>1)
      S(a)=-P(a)+i*Q(a);
   end
end
% P(2)=0.5;Q(2)=0.2;
% S(2)=-0.5+i*0.2;
% P(3)=0.4;Q(3)=0.3;
% S(3)=-0.4+i*0.3;
% P(4)=(0.05-0.0033)*rand;


reV1=input('Enter Real V1:');
imV1=input('Enter Imaginary V1:');
V1(1)=complex(reV1,imV1);
% V1(1)=1.06+i*0;
```

```
reV2=input('Enter Real V2:');

imV2=input('Enter Imaginary V2:');

V2(1)=complex(reV2,imV2);

% V2(1)=1+i*0;



reV3=input('Enter Real V3:');

imV3=input('Enter Imaginary V3:');

V3(1)=complex(reV3,imV3);

% V3(1)=1+i*0;



reV4=input('Enter Real V4:');

imV4=input('Enter Imaginary V4:');

V4(1)=complex(reV4,imV4);

% V4(1)=1.04+i*0;



% Assume bus 1=slack, bus 2,3=PQ and bus 4=PV bus

% Calculation of bus voltages

%epsil=input('Enter the value of tolerance:');
```

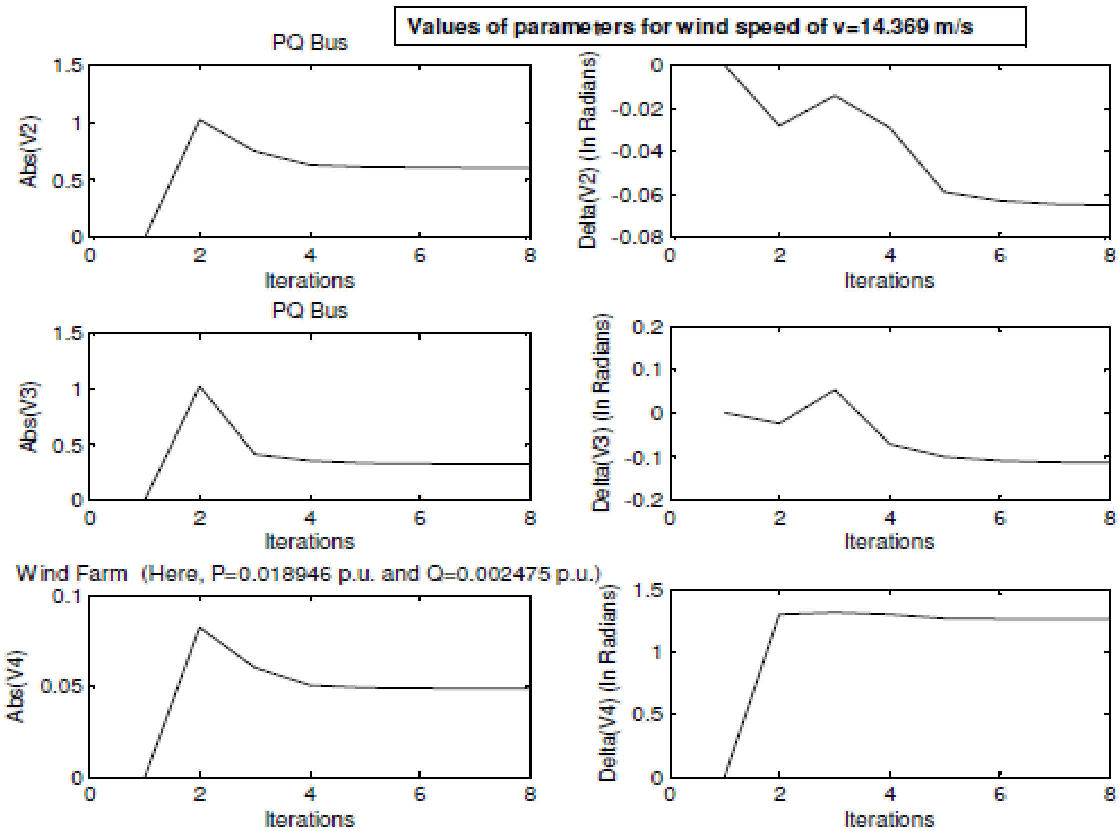
```
epsil=0.001;

error=1;

a=2;

Q4up=0.6*0.05/0.8;   % Active power (P) generated by wind farm for v=20m/s is 5MW.

Q4low=0.6*0.0033/0.8;% Active power (P) generated by wind farm for v=8m/s is 0.33MW.

while(error>epsil)

  R4=real(Y(4,1))*real(V1(1))+real(Y(4,2))*real(V2(a-1))+real(Y(4,3))*real(V3(a-
1))+real(Y(4,4))*real(V4(a-1))-imag(Y(4,1))*imag(V1(1))-imag(Y(4,2))*imag(V2(a-1))-
imag(Y(4,3))*imag(V3(a-1))-imag(Y(4,4))*imag(V4(a-1));

  I4=real(Y(4,1))*imag(V1(1))+real(Y(4,2))*imag(V2(a-1))+real(Y(4,3))*imag(V3(a-
1))+real(Y(4,4))*imag(V4(a-1))+imag(Y(4,1))*real(V1(1))+imag(Y(4,2))*real(V2(a-
1))+imag(Y(4,3))*real(V3(a-1))+imag(Y(4,4))*real(V4(a-1));

  Q(4)=imag(V2(a-1))*R4-real(V2(a-1))*I4;

  if(Q(4)>Q4up)

    Q(4)=Q4up;

  end

  if(Q(4)<Q4low)

    Q(4)=Q4low;

  end
```

```
S(4)=P(4)-i*Q(4);


V2(a)=S(2)/conj(V2(a-1));

V2(a)=V2(a)-(Y(2,1)*V1(1)+Y(2,3)*V3(a-1)+Y(2,4)*V4(a-1));

V2(a)=V2(a)/Y(2,2);

abV2(a)=abs(V2(a));

anV2(a)=angle(V2(a));


V3(a)=S(3)/conj(V3(a-1));

V3(a)=V3(a)-(Y(3,1)*V1(1)+Y(3,2)*V2(a)+Y(3,4)*V4(a-1));

V3(a)=V3(a)/Y(3,3);

abV3(a)=abs(V3(a));

anV3(a)=angle(V3(a));


V4(a)=S(4)/conj(V4(a-1));

V4(a)=V4(a)-(Y(4,1)*V1(1)+Y(4,2)*V2(a)+Y(4,3)*V3(a));

V4(a)=V2(a)/Y(4,4);

abV4(a)=abs(V4(a));
```

```
    anV4(a)=angle(V4(a));


    err2(a)=abs(V2(a)-V2(a-1));

    err3(a)=abs(V3(a)-V3(a-1));

    err4(a)=abs(V4(a)-V4(a-1));


    errmat=[err2(a) err3(a) err4(a)];

    error=max(errmat);

    a=a+1;

end


disp('Wind Velocity (wvel)(in m/s):');

wvel=((P(4)*10^8)/638.6)^(1/3)

V2Final=V2(a-1)

V3Final=V3(a-1)

V4Final=V4(a-1)

a

subplot(3,2,1);
```

```
plot(abV2)

subplot(3,2,2);

plot(anV2)

subplot(3,2,3);

plot(abV3)

subplot(3,2,4);

plot(anV3)

subplot(3,2,5);

plot(abV4)

subplot(3,2,6);

plot(anV4)


% Important Notes:
% There are 1000 wind mills in this Wind Farm. So, output of one wind mill =
% P_one_windmill=P/1000
% P_one_windmill=0.6386*(cube of wind velocity (in m/s))=0.6386*wvel^3
% where P_one_windmill is in Watt.
```

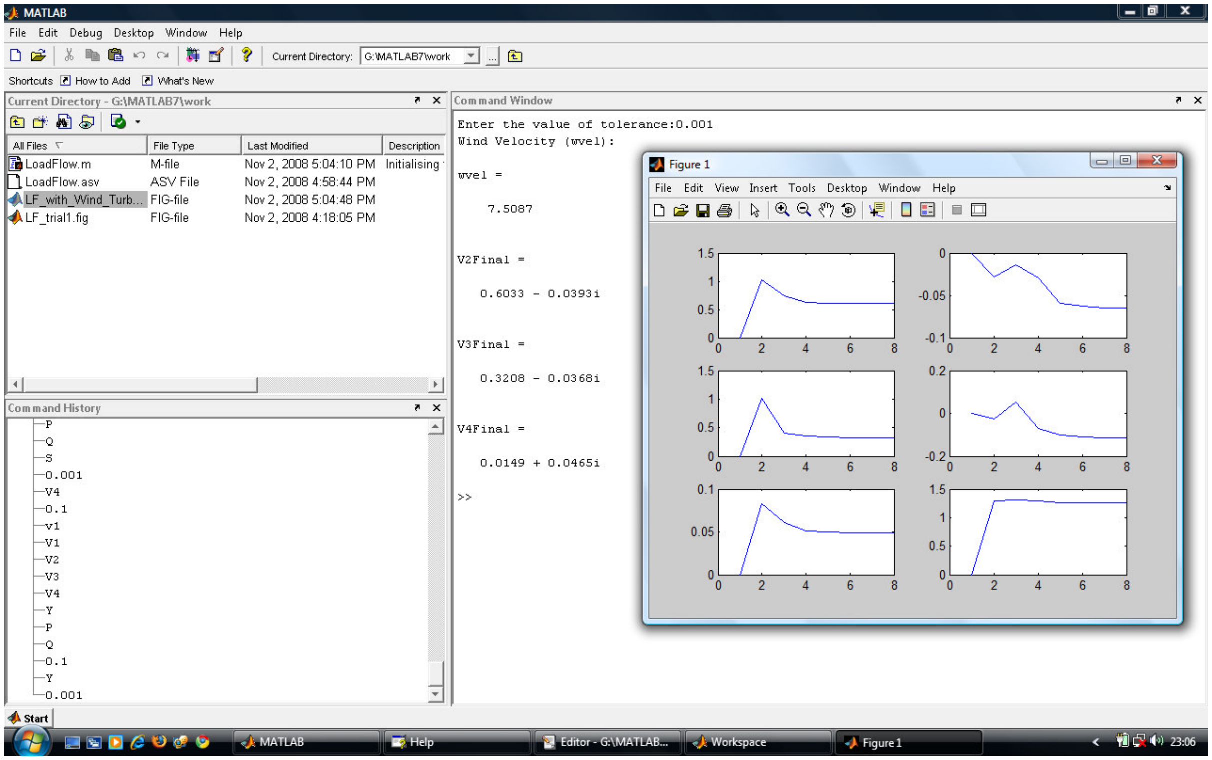
Output of program:



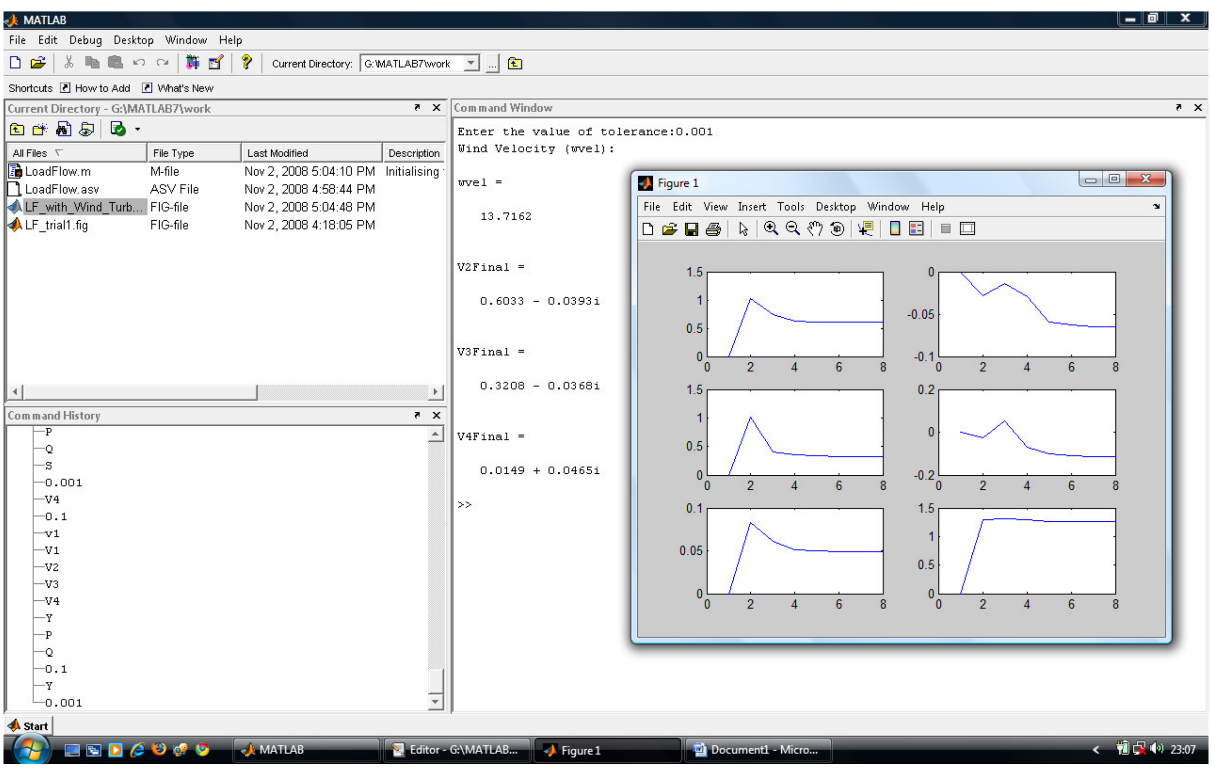
Analysis of Result:

This program performs load flow analysis of a grid connected wind turbine. Active power 'P' contributed by wind turbine is a function of cube of velocity where velocity is limited between 8m/s to 20m/s. This program generates a random velocity between the limits and performs load-flow, thus calculating the voltage Abs (V2), Abs (V3) & Abs (V4) and Delta (V2), Delta (V3) & Delta (V4) as shown above.

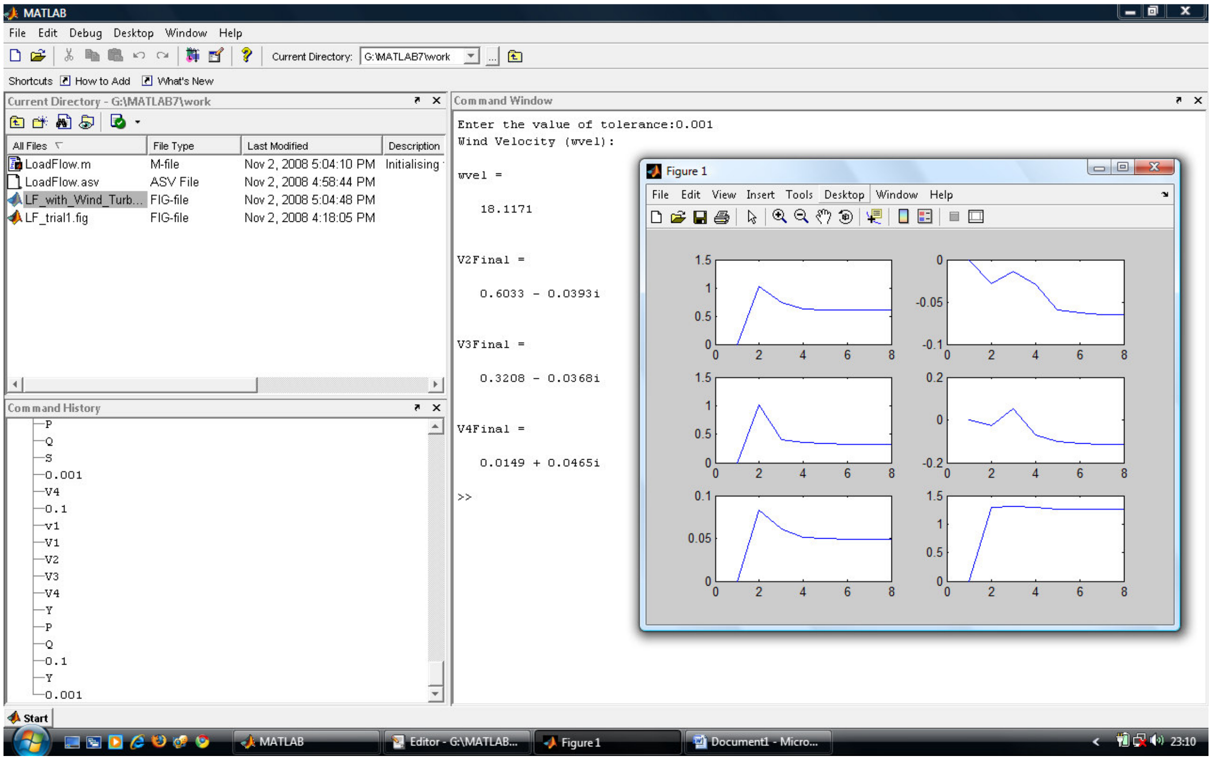
RUN 1:


Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
7.5087
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
>>

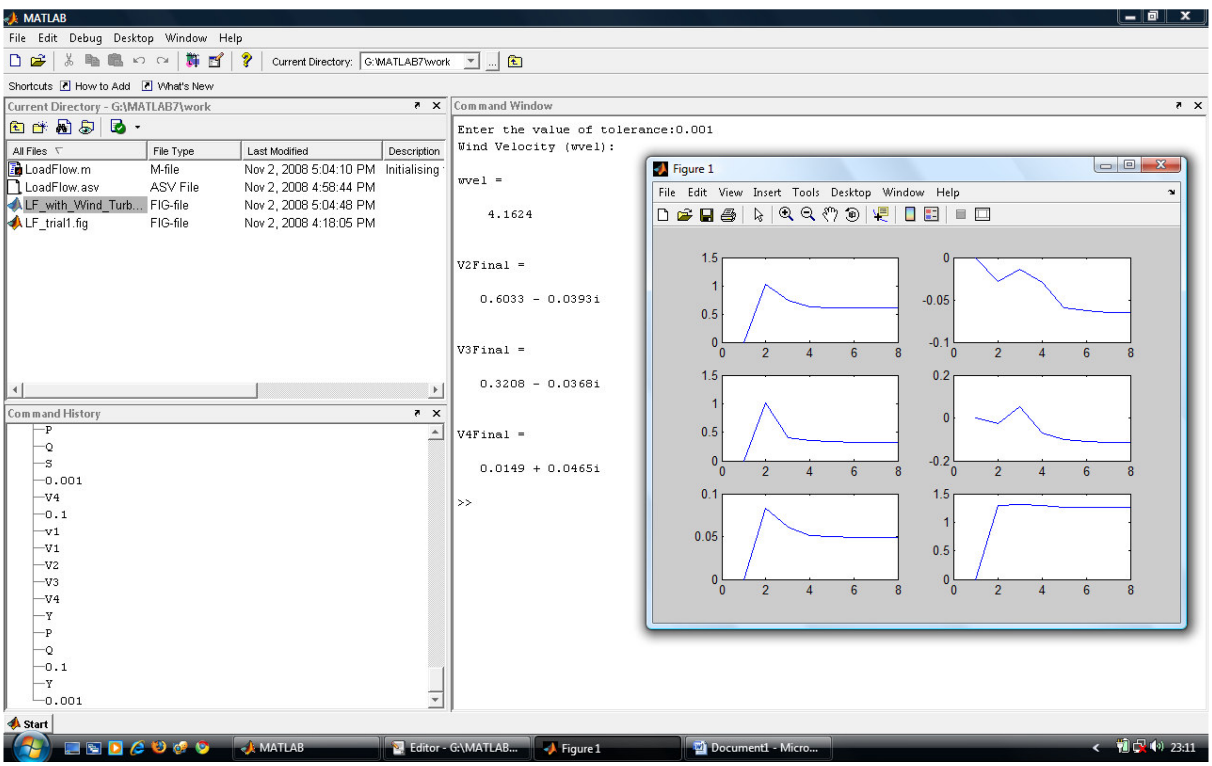
RUN 2:


Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
13.7162
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
>>

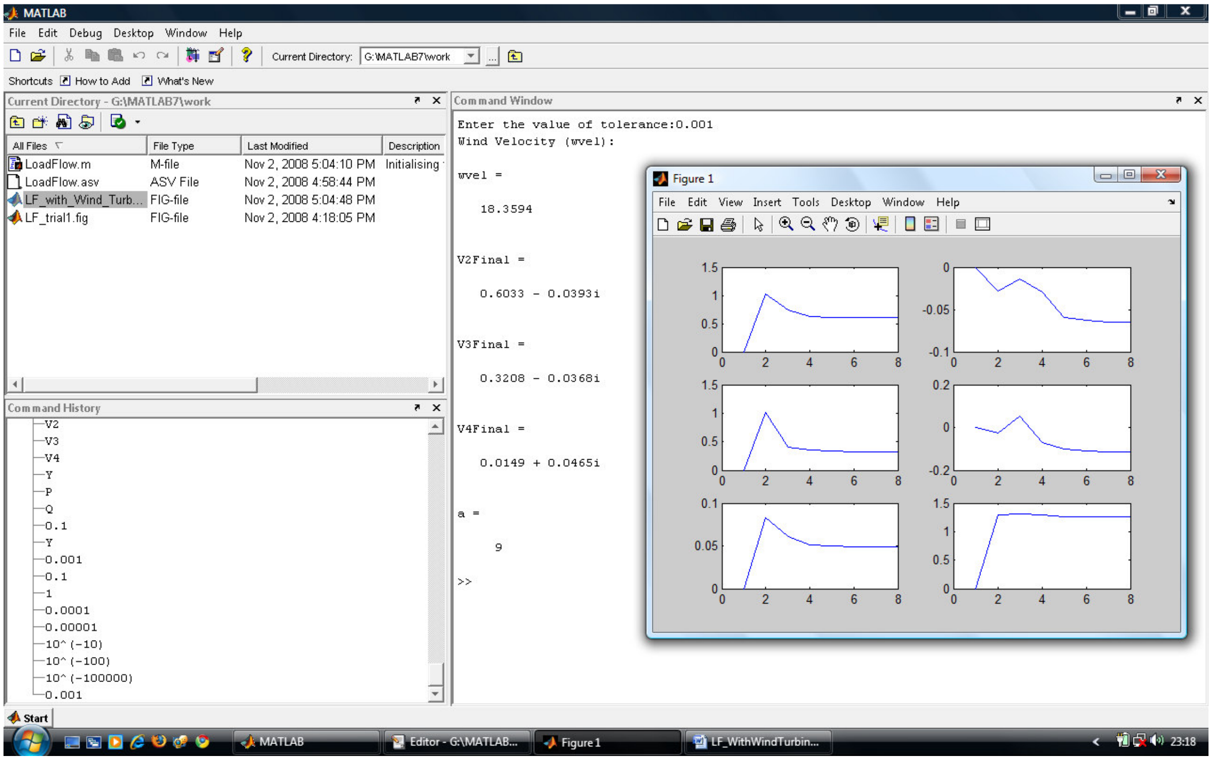
RUN 3:


MATLAB
File Edit Debug Desktop Window Help
Current Directory: G:\MATLAB7\work
Current Directory - G:\MATLAB7\work
All Files
File Type
Last Modified
Description
LoadFlow.m
M-file
Nov 2, 2008 5:04:10 PM
Initialising
LoadFlow.asv
ASV File
Nov 2, 2008 4:58:44 PM
LF_with_Wind_Turb...
FIG-file
Nov 2, 2008 5:04:48 PM
LF_trial1.fig
FIG-file
Nov 2, 2008 4:18:05 PM
Command History
Command Window
Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
18.1171
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
>>
Figure 1

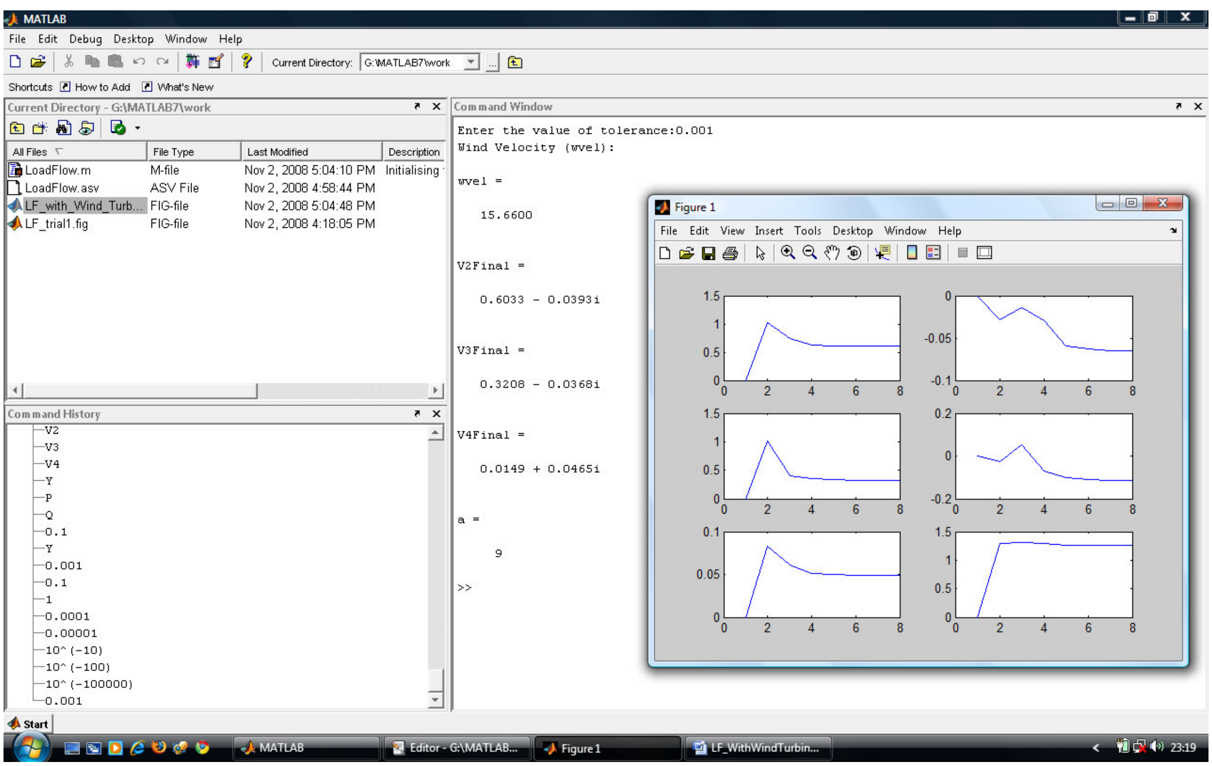
RUN 4:


MATLAB
File Edit Debug Desktop Window Help
Current Directory: G:\MATLAB7\work
Current Directory - G:\MATLAB7\work
All Files
File Type
Last Modified
Description
LoadFlow.m
M-file
Nov 2, 2008 5:04:10 PM
Initialising
LoadFlow.asv
ASV File
Nov 2, 2008 4:58:44 PM
LF_with_Wind_Turb...
FIG-file
Nov 2, 2008 5:04:48 PM
LF_trial1.fig
FIG-file
Nov 2, 2008 4:18:05 PM
Command History
Command Window
Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
4.1624
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
>>
Figure 1

RUN 5:


Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
18.3594
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
a =
9
>>

RUN 6:


Enter the value of tolerance:0.001
Wind Velocity (wvel):
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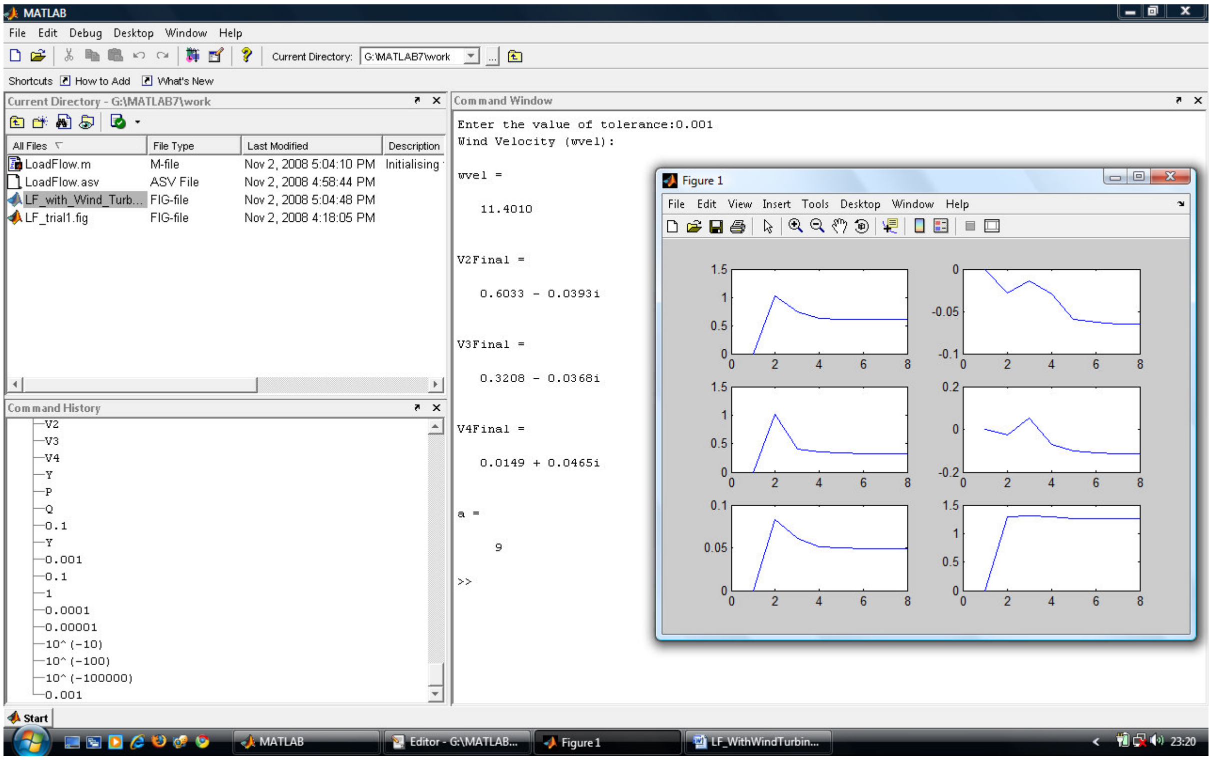
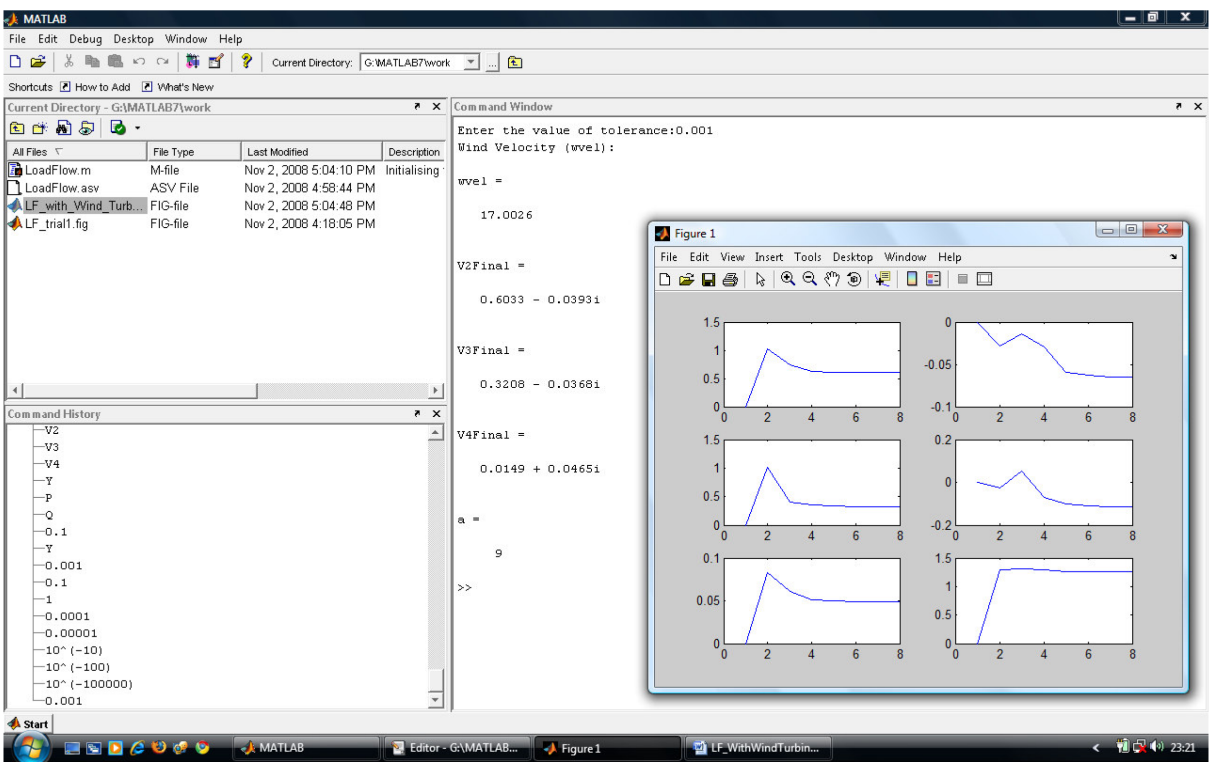
15.6600
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
a =
9
>>

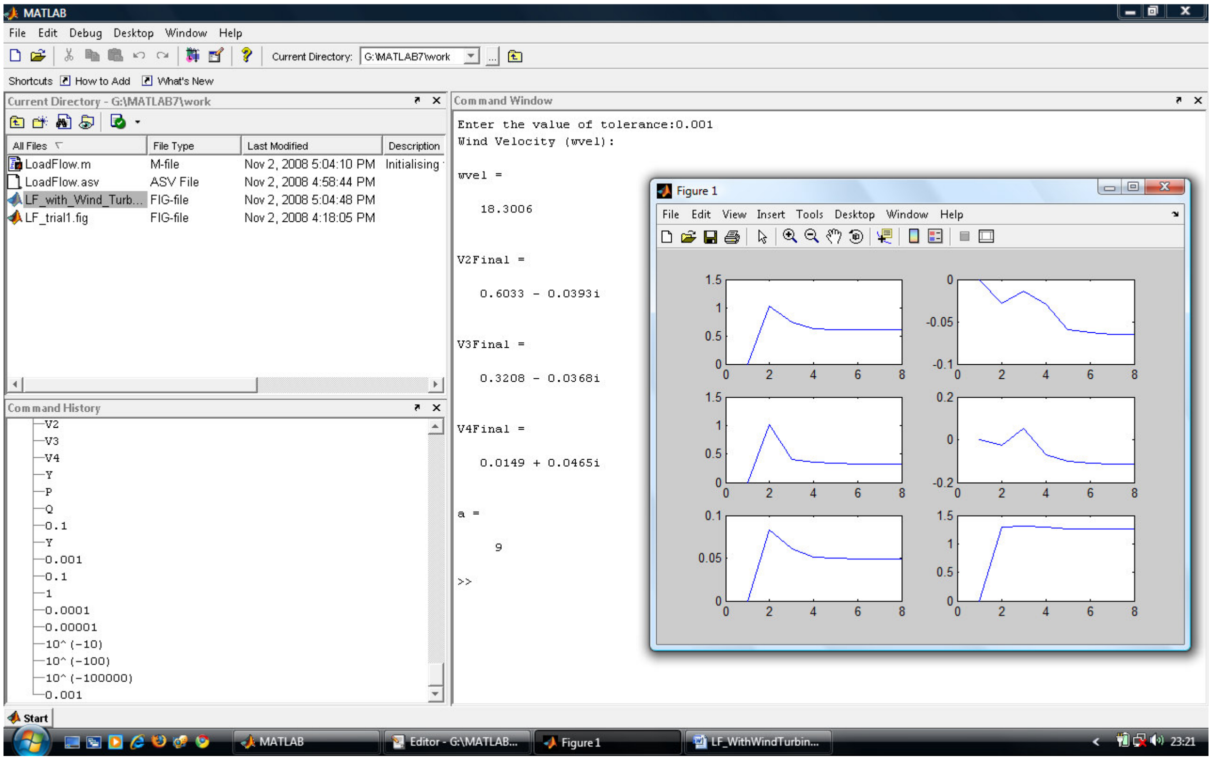
RUN 7:


MATLAB
Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
11.4010
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
a =
9
Figure 1

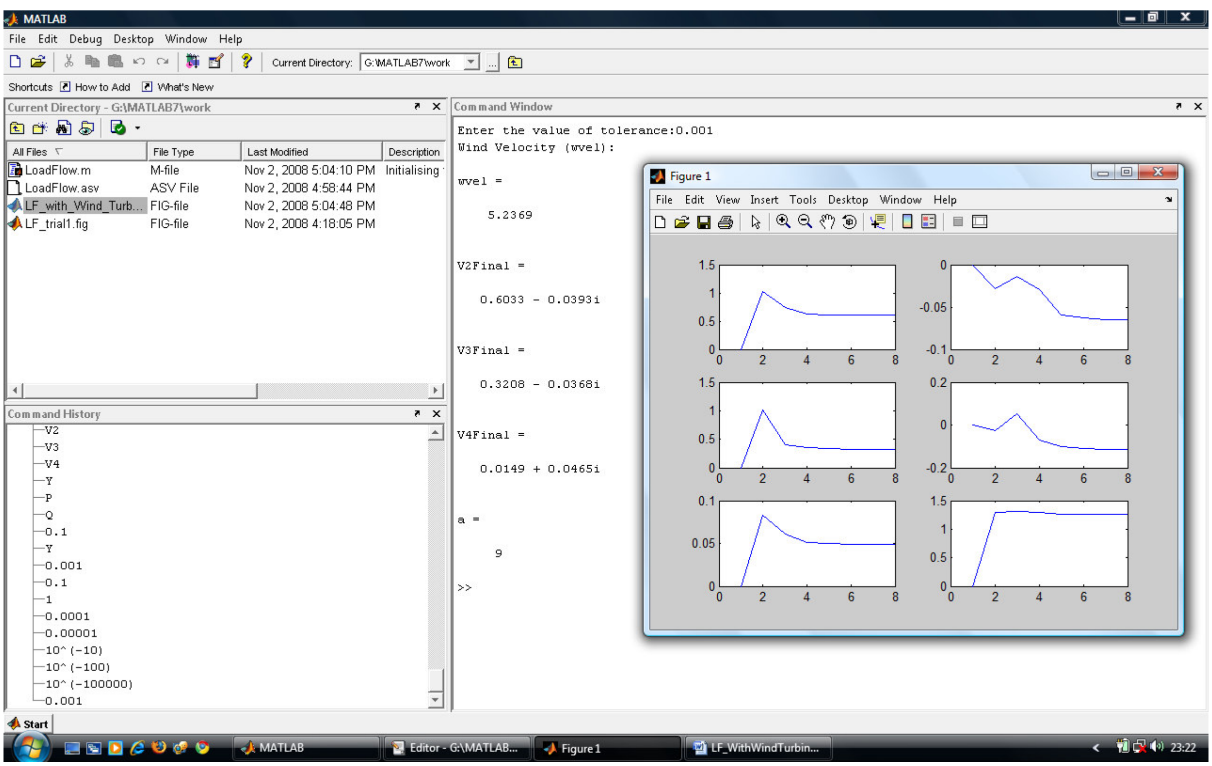
RUN 8:


MATLAB
Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
17.0026
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
a =
9
Figure 1

RUN 9:


Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
18.3006
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
a =
9

RUN 10:


Enter the value of tolerance:0.001
Wind Velocity (wvel):
wvel =
5.2369
V2Final =
0.6033 - 0.0393i
V3Final =
0.3208 - 0.0368i
V4Final =
0.0149 + 0.0465i
a =
9

Chapter 2

Introduction to solar energy

Introduction:

Solar energy is an important, clean, cheap and abundantly available renewable energy. It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m^2.Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc. For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the heliostats should be calculated.

Units of solar power and solar energy:

In SI units, energy is expressed in Joule. Other units are angley and Calorie where

$$1 \text{ angley} = 1 \text{ Cal/cm}^2\text{.day}$$

$$1 \text{ Cal} = 4.186 \text{ J}$$

For solar energy calculations, the energy is measured as an hourly or monthly or yearly average and is expressed in terms of kJ/m^2/day or kJ/m^2/hour.

Solar power is expressed in terms of W/m^2 or kW/m^2.

Essential subsystems in a solar energy plant:

1. **Solar collector or concentrator**: It receives solar rays and collects the energy. It may be of following types:
   a) Flat plate type without focusing
   b) Parabolic trough type with line focusing
   c) Paraboloid dish with central focusing
   d) Fresnel lens with centre focusing
   e) Heliostats with centre receiver focusing
2. **Energy transport medium**: Substances such as water/ steam, liquid metal or gas are used to transport the thermal energy from the collector to the heat exchanger or thermal storage. In solar PV systems energy transport occurs in electrical form.
3. **Energy storage**: Solar energy is not available continuously. So we need an energy storage medium for maintaining power supply during nights or cloudy periods. There are three major types of energy

storage: a) Thermal energy storage; b) Battery storage; c) Pumped storage hydro-electric plant.

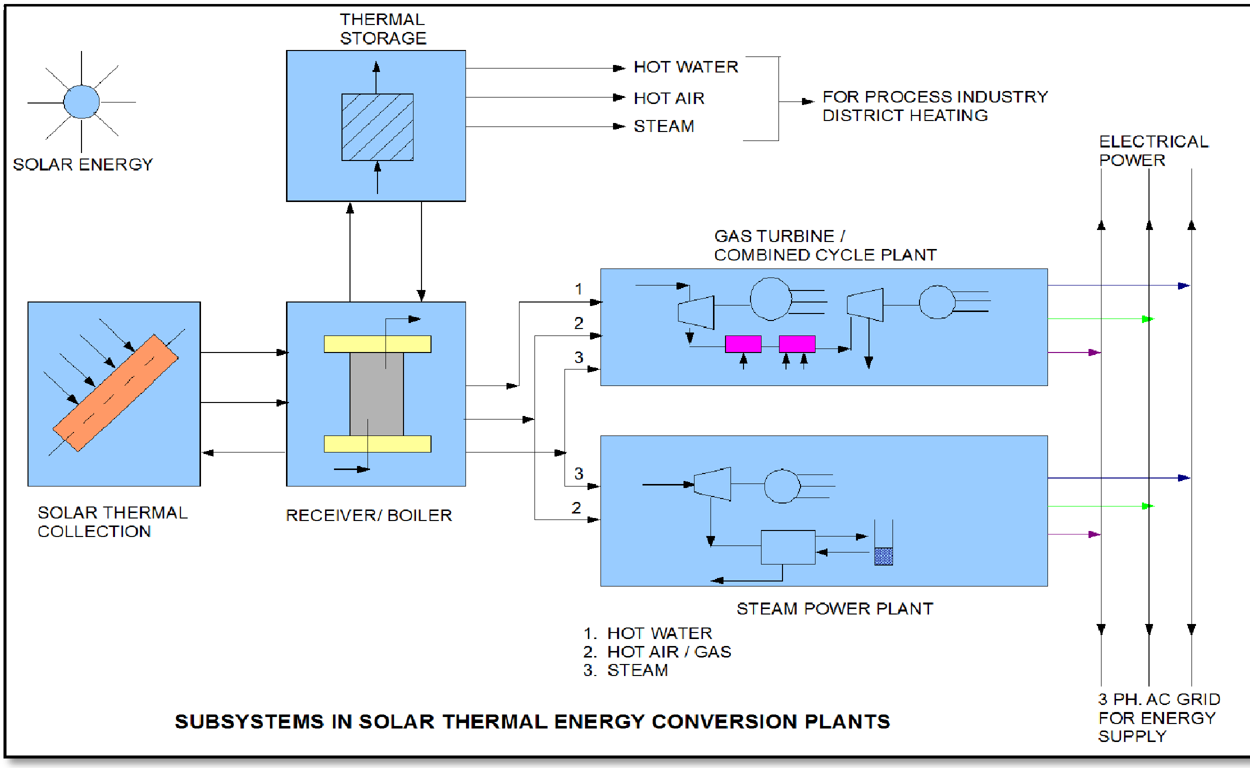


Figure 1: Subsystems in solar thermal energy conversion plants

4. **Energy conversion plant**: Thermal energy collected by solar collectors is used for producing steam, hot water, etc. Solar energy converted to thermal energy is fed to steam-thermal or gas-thermal power plant.
5. **Power conditioning, control and protection system**: Load requirements of electrical energy vary with time. The energy supply has certain specifications like voltage, current, frequency, power etc. The power conditioning unit performs several functions such as control, regulation, conditioning, protection, automation, etc.
6. **Alternative or standby power supply**: The backup may be obtained as power from electrical network or standby diesel generator.

Energy from the sun:

The sun radiates about 3.8 x 10^{26} W of power in all the directions. Out of this about 1.7 x 10^{17} W is received by earth. The average solar radiation outside the earth's atmosphere is 1.35 kW/m^2 varying from 1.43 kW/m^2 (in January) to 1.33 kW/m^2 (in July).

Solar constant (S):

Solar constant is the solar radiation received per unit area normal to the sun's rays in a space outside the earth's atmosphere. In SI units the value of S is 1353 W/m^2.

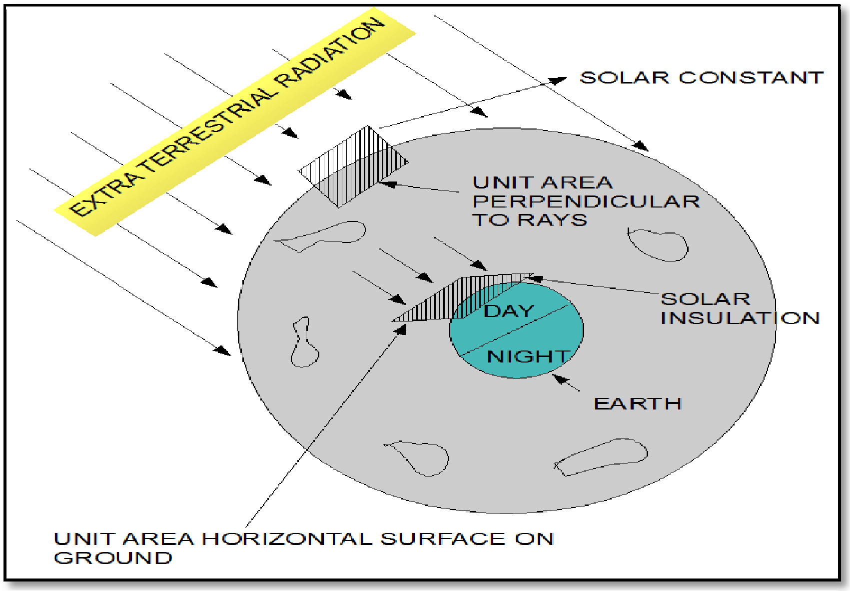


Figure 2: Solar Constant

Clarity index:

While passing through the atmosphere, the beam radiation from the sun is partly absorbed and partly scattered by the atmospheric dust, gases, cloud, moisture etc. On a moderate cloudy day, reduction is 10-50%. During dark and cloudy day, radiation reduces to 1%. Flat plate collectors are better suited than focusing collectors for diffused sunlight (cloudy atmosphere). The effect of atmospheric conditions on the beam radiation is expressed by Atmospheric Clarity Index (ACI) given by

$$\text{ACI} = \frac{Solar\ Insolation\ (\frac{W}{m^2})}{Solar\ \text{Constant}\ (\frac{W}{m^2})}$$

Solar radiation data for India:

India is situated in the Northern hemisphere of earth within latitudes 7^{O}N and 37.5^{O}N. The average solar radiation values for India are between 12.5 and 22.7 MJ/m^2.day. Peak radiation is received in some parts of Rajasthan and Gujarat. Radiation falls by 60% during monsoon.

Solar insolation:

Solar insolation is the solar radiation received on a flat, horizontal surface at a particular location on earth at a particular instant of time. It depends on the following parameters:

1. Daily variation (Hour angle)
2. Seasonal variation and geographic location of the particular surface.
3. Atmospheric clarity
4. Shadows of trees, tall structures, adjacent solar panels, etc.
5. Degree of latitude of the location
6. Area of exposed surface, m^2
7. Angle of tilt of solar panel.

Modified Angstrom's equation for Average Daily Global Radiation:

Modified Angstrom equation is used to determine the radiation at different places on earth. It is given as

$$\frac{H_g}{H_o} = a + b\,\frac{L_h}{L_m}$$

Where

- H_g= Daily Global Radiation for a flat surface at the location for the particular month kJ/m2. day
- H_o = Daily extra-terrestrial radiation, (mean value for the month). It is calculated from solar constant and expressed in kJ/m2.day.
- L_h = Length of day (average for the month) (in hours)
- L_m = Longest day of the month hours
- a,b = constants for various cities of the world.

We have $$H_o = \frac{H_{o1}+H_{o2}+\cdots+H_{o30}}{30}$$

and individual values of H_{o1}, H_{o2}, H_{o3}... H_{o30} are calculated from

$$H_o = I_{sc}\{1+0.033.\cos\left(\frac{360n}{365}\right)\}\int[(\sin\varphi.\sin\delta) + (\cos\varphi.\cos\delta.\cos\omega)]\,dt$$

where

Φ = angle of latitude of the location. By convention φ is considered positive in Northern hemisphere.

δ = angle of declination. It is the angle between line joining centers of the sun and the earth and the equatorial plane.

ω = hour angle. It is the angle tracted by sun in 1 hour with reference to 12 noon and is equivalent to 15^0 per hour.

I_{sc}= Solar constant in terms of kJ/m^2.hr= S x 3600 =1.353 x 3600 ≈ 4871

H_g= Daily Global Radiation for a flat surface at the location for the particular month kJ/m^2. Day

H_o = Daily extra-terrestrial radiation, mean value for the month, calculated from solar constant kJ/m^2.day

L_h = Length of day (average for the month) (in hours)

L_m = Longest day of the month hours

a and b are obtained from actual measurements at the particular location.

Chapter 3

Solar thermal energy conversion systems

Introduction:

A solar thermal collector system gathers the heat from the solar radiation and gives it to the heat transport fluid. The heat-transport fluid receives the heat from the collector and delivers it to the thermal storage tank, boiler steam generator, heat exchanger etc. Thermal storage system stores heat for a few hours. The heat is released during cloudy hours and at night. Thermal-electric conversion system receives thermal energy and drives steam turbine generator or gas turbine generator. The electrical energy is supplied to the electrical load or to the AC grid. Applications of solar thermal energy systems range from simple solar cooker of 1 kW rating to complex solar central receiver thermal power plant of 200 MWe rating.

Solar thermal collectors:

As solar power has low density (kW/m^2), therefore large area on the ground is covered by collectors. Flat plate collectors are used for low temperature applications. For achieving higher temperature of transport fluid, the sun rays must be concentrated and focused.

Concentration Ratio (CR):

$$\text{CR} = \frac{Solar\ radiation\ on\ surface\ (\frac{kW}{m^2})}{Solar\ radiation\ at\ focus\ on\ surface\ of\ collector\ (\frac{kW}{m^2})}$$

For flat plate collectors, CR = 1. Using heliostats with sun-tracking in two planes, we obtain CR of the order of 1000. CR up to 100 can be achieved by using parabolic trough collectors with sun tracking in one plane.

Collector efficiency (η):

The performance of a collector is evaluated in terms of its collector efficiency which is given as

$$\eta = \frac{Energy\ collected\ by\ the\ collector\ (J)}{Energy\ incident\ on\ the\ collector\ (J)}$$

For constant solar radiation (kW/m^2), the collector efficiency decreases with the increasing difference between the collector temperature and the outside temperature.

Flat plate collector:

Flat plate collector absorbs both beam and diffuse components of radiant energy. The absorber plate is a specially treated blackened metal surface. Sun rays striking the absorber plate are absorbed causing rise of temperature of transport fluid. Thermal insulation behind the absorber plate and transparent cover sheets (glass or plastic) prevent loss of heat to surroundings.

Applications of flat plate collector:

1. Solar water heating systems for residence, hotels, industry.
2. Desalination plant for obtaining drinking water from sea water.
3. Solar cookers for domestic cooking.
4. Drying applications.
5. Residence heating.

Losses in flat plate collector:

1. **Shadow effect**: Shadows of some of the neighbor panel fall on the surface of the collector where the angle of elevation of the sun is less than 15^O (sun-rise and sunset).

   $$\text{Shadow factor} = \frac{Surface\ of\ the\ collector\ receiving\ light}{Total\ surface\ of\ the\ collector}$$

Shadow factor is less than 0.1 during morning and evening. The effective hours of solar collectors are between 9AM and 5PM.

2. **Cosine loss factor**: For maximum power collection, the surface of collector should receive the sun rays perpendicularly. If the angle between the perpendicular to the collector surface and the direction of sun rays is θ, then the area of solar beam intercepted by the collector surface is proportional to cos θ.
3. **Reflective loss factor**: The collector glass surface and the reflector surface collect dust, dirt, moisture etc. The reflector surface gets rusted, deformed and loses the shine. Hence, the efficiency of the collector is reduced significantly with passage of time.

Maintenance of flat plate collector:

1. Daily cleaning
2. Seasonal maintenance (cleaning, touch-up paint)
3. Yearly overhaul (change of seals, cleaning after dismantling)

Parabolic trough collector:

Parabolic trough with line focusing reflecting surface provides concentration ratios from 30 to 50. Hence, temperature as high as $300^{O}C$ can be attained. Light is focused on a central line of the parabolic trough. The pipe located along the centre line absorbs the heat and the working fluid is circulated trough the pipe.

Paraboloid dish collectors:

The beam radiation is reflected by paraboloid dish surface. The point focus is obtained with CR (above 1000) and temperatures around $1000^{O}C$.

Chapter 4

Solar energy storage

Introduction:

Unfortunately, the time when solar energy is most available will rarely coincide exactly with the demand for electrical energy, though both tend to peak during the day light hours. There is also the problem of clouds with photovoltaic plants, and cloud cover for several days may result in substantially lowered electrical output compared to high insolation cloud-free days. During such days energy previously stored during high insolation times could be used to provide a continuous electrical output or thermal output.

Solar energy storage systems:

Solar energy storage systems are classified as shown in figure below.

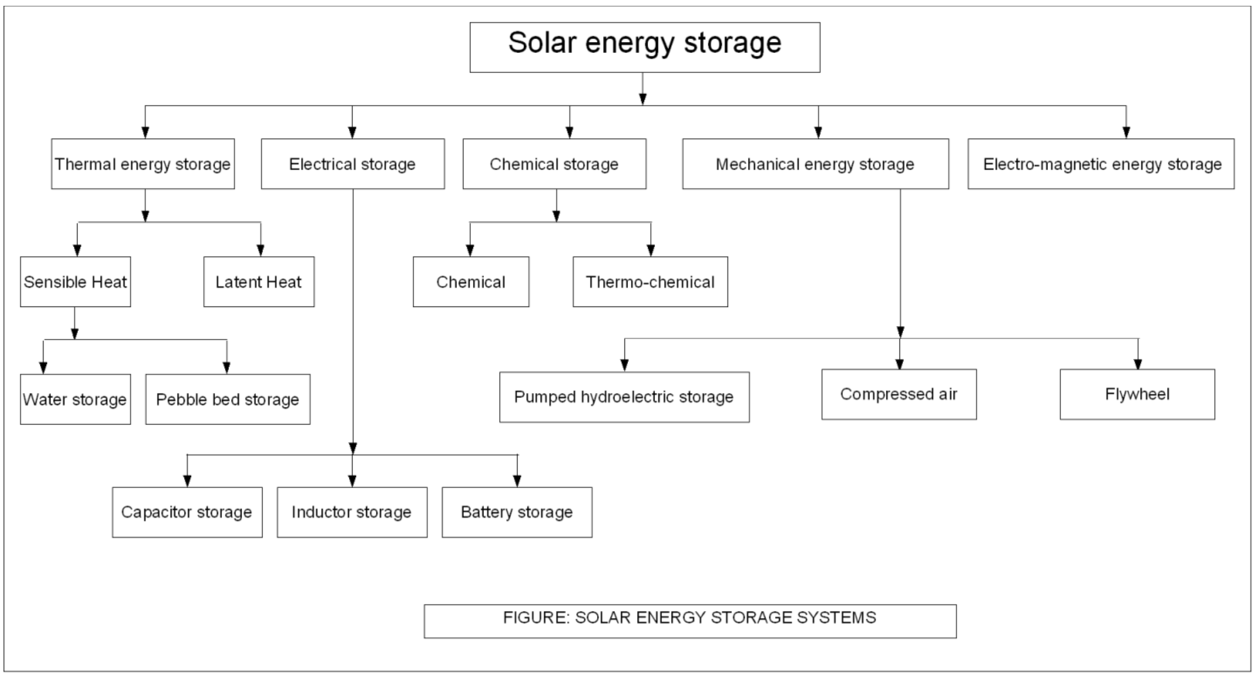


Figure 1: Types of solar energy storage systems

Thermal storage:

Energy can be stored by heating, melting or vaporization of material; and the energy becomes available as heat, when the process is reversed.

Sensible heat storage:

Storage by causing a material to rise in temperature is called sensible heat storage. It involves a material that undergoes no change in phase. The basic equation for an energy storage unit operating over a finite temperature difference is

$Q_S = (m.\ C_P)_S(T_1\text{-}T_2) = (m.\ C_P)_S\ \Delta T$

$$or\ \frac{Q_S}{V} = \rho\, Cp\ \Delta T$$

where ρ is the density of the storage medium.

Water storage:

The most common heat transfer fluid for a solar system is water, and the easiest way to store thermal energy is by storing the water directly in a well insulated tank.

Features of water storage are:

1. It is an inexpensive, readily available and useful material to store sensible heat.
2. It has high thermal storage capacity.
3. Energy addition and removal from this type of storage is done by medium itself, thus eliminating any temperature drop between transport fluid and storage medium.
4. Pumping cost is small.

Pebble bed storage:

Here, rock, gravel or crushed stone in a bin provides a large, cheap heat transfer surface. Rock is more easily contained than water. It acts as its own heat exchanger, which reduces total system cost. Rock can be easily used for thermal storage at high temperatures (above $100^{O}C$). If water storage is used above $100^{O}C$, then pressurized storage is required to contain steam. Hence, pebble bed storage has low cost of storage material. This type of storage system has been used in the solar houses or with hot air collector system.

Latent heat storage (Phase change energy storage):

Here, heat is stored in a material when it melts and extracted from the material when it freezes. Glauber's salt ($Na_2SO_4.10H_2O$) changes phase from solid to liquid requires lesser energy than those from liquid to gas. It decomposes at about $32^{O}C$ releasing 56kCal/kg.

Electrical storage:

1. Energy stored in capacitor is given as

$$H=\frac{1}{2} V\varepsilon E^2$$

Where V = volume of dielectric

E = electric field strength

Electric field strength is limited by the breakdown strength (E_{br}) of the dielectric (e.g. mica).

As the conductivity of dielectric is finite, therefore losses occur in the storage battery.

2. Inductors store energy at low voltage and high current. The energy is given by

$$H=\frac{1}{2} V\mu {H_m}^2$$

Where μ = permeability of material

H_m = magnetic flux density

For H to be large, both μ and H_m should be large. Higher magnetic fields exert large forces on structure. So the structure must be mechanically strong.

3. Battery storage:
    1. Energy efficiency (η) of battery storage is given as

$$\eta = \frac{\int_0^{t_1} I_1 E_1 dt}{\int_0^{t_2} I_2 E_2 dt}$$

Where I_1= battery discharge current

E_1=battery discharge terminal voltage

I_2 = battery charging current

E_2= battery charging terminal voltage

t_1 = battery discharging time

t_2 = battery discharging time

    2. Cycle life of battery storage is the number of times the battery can be charged and discharged under specified conditions.

Chemical storage:

Solar energy can be stored chemically in the form of fuel. The battery is charged photo-chemically and discharged electrically whenever needed. It is also possible to electrolyze water with solar electricity generated, store $H_2$and O_2 and recombine in a fuel cell to regain electrical energy. Solar energy can be converted into methane by anaerobic fermentation of algae. 1km^2 of algae field can produce methane carrying 4MW of solar energy.

Thermo-chemical energy storage (Reversible):

Thermo-chemical energy storage systems are suitable for medium or high temperature applications only. Their major advantage is high energy density at ambient temperatures for long periods without thermal losses.

Pumped hydroelectric storage of solar energy:

Electric power in excess of the immediate demand is used to pump water from a supply (e.g. like, river or reservoir) at a lower level to a reservoir at a higher level. When power demand exceeds the supply, the water is allowed to flow back down through a hydraulic turbine which drives an electric generator. Efficiency of pumped storage is around 70%.

Compressed air storage:

Here, the extra energy is stored in the form of a compressed air volume. When energy demand is high, this air can be used to drive wind turbine to generate electric power.

Flywheel storage:

A flywheel driven by an electric motor during off peak hours stores mechanical energy as it gains speed. The rotational energy of flywheel is used to drive generator to produce electricity.

CHAPTER 5

Solar power plant

Introduction:

Solar electrical power plants require large collection field covering several km^2 area, complex and costly sun-tracking system for large heliostats, long piping system and large thermal storage system.

Types of solar power plant:

1. Solar distributed collector power plants
2. Solar central receiver power plants

Solar distributed collector power plants:

In distributed receiver power plants, parabolic trough collectors with line focus are most commonly used. The sun rays are reflected by parabolic or cylindrical troughs. The reflected rays are focused on linear conduit (pipe) located along the axis of the trough.

Figure 1 shows a schematic diagram of a distributed collector solar thermal power plant. The major components are the following:

1. Trough collectors distributed in the solar field
2. Piping system for primary heat transport loop
3. Heat transport fluid pump
4. Boiler cum steam generator
5. Secondary (working) fluid loop (steam)
6. Steam turbine
7. Turbo-generator
8. Condenser
9. Hot condensate pump – Water loop
10. Feed water heater- Steam loop
11. Boiler feed pump

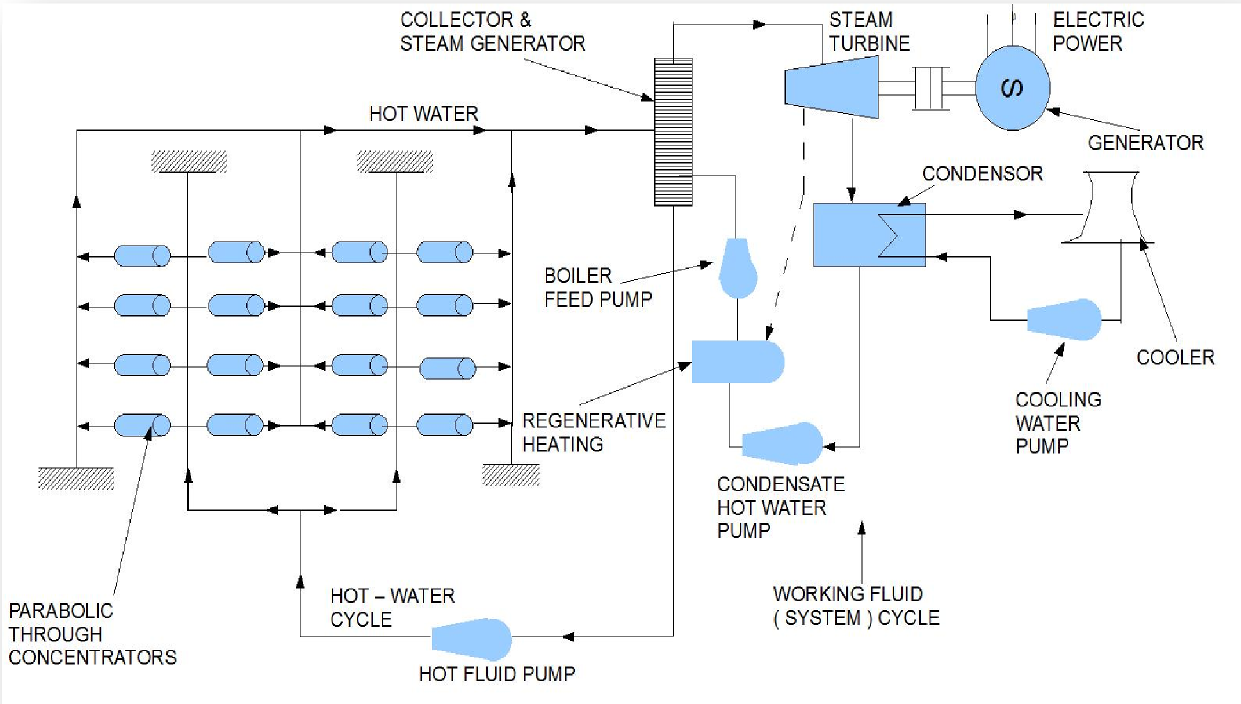


Figure 1: Solar distributed collector power plants

Solar central receiver power plants:

Central receiver scheme is used to design large solar thermal power plant in the range of 50-200 MW (Figure 2). The high capacity is possible due to high temperature steam in the central receiver results in high efficiency of plants. In this plant, several heliostats are located on the ground level. The heliostat reflects sun rays towards a central receiver mounted on a tall tower (Figure 3). The large central receiver power plant is usually built with modular concept. Each power plant may have 2 to 10 modules. Each module may be rated for 10MWe to 100MWe. Reference data of a 100 MWe Solar Central Receiver Power Plant is given in appendix Table A-6.

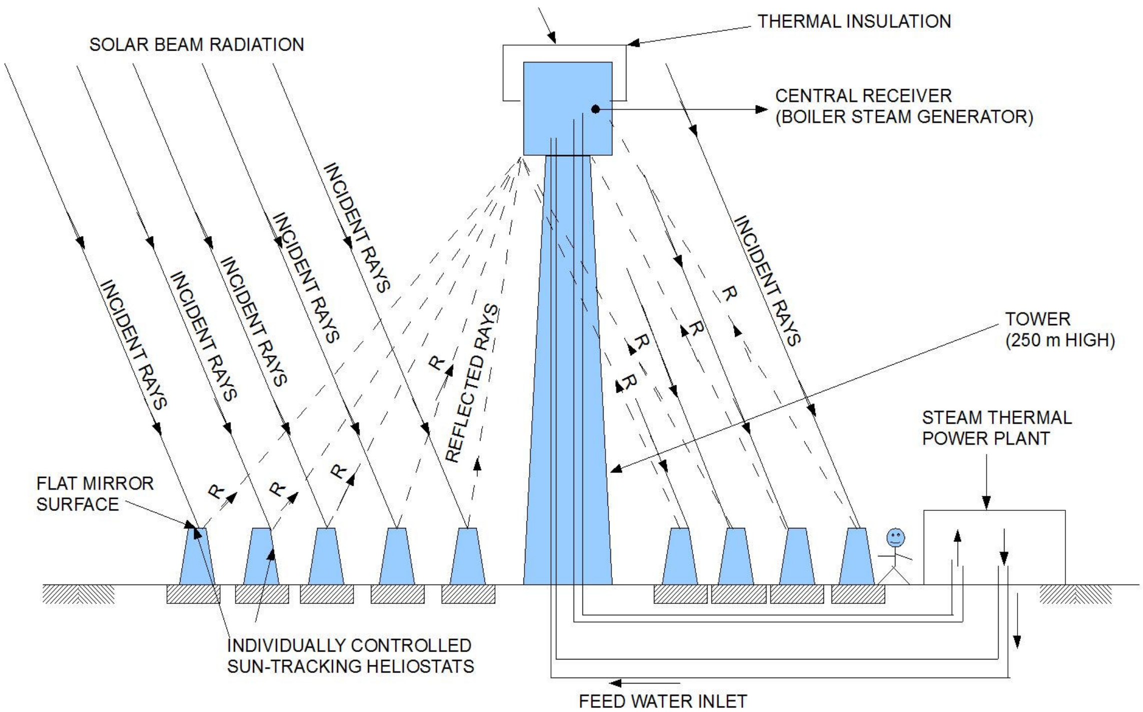


Figure 2: Solar central receiver power plants

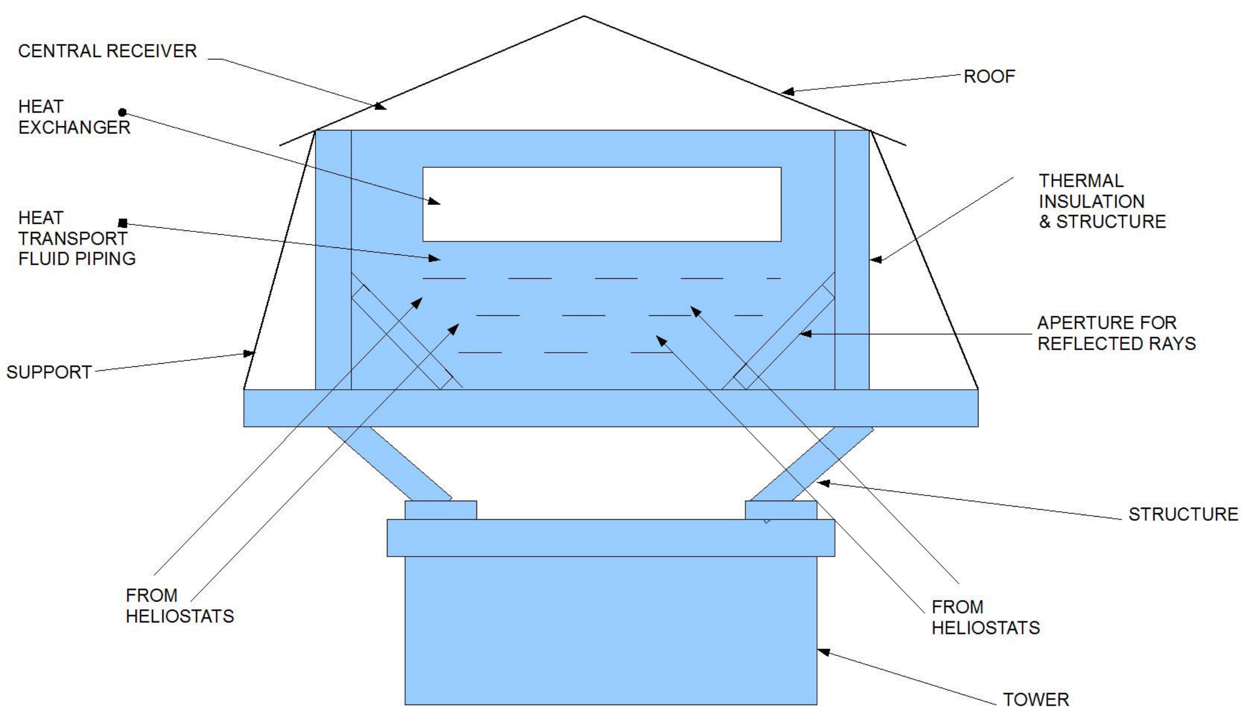


Figure 3: Central receiver

Solar pond thermal plant:

Solar pond (Figure 4-4) is a specially built large shallow reservoir of water. The water gets heated by the sunlight. The bottom of the pond is painted black for absorption of heat. The water is made saline by adding salt. Lower layers are of high salt concentration whereas upper layers are of low salt concentration.

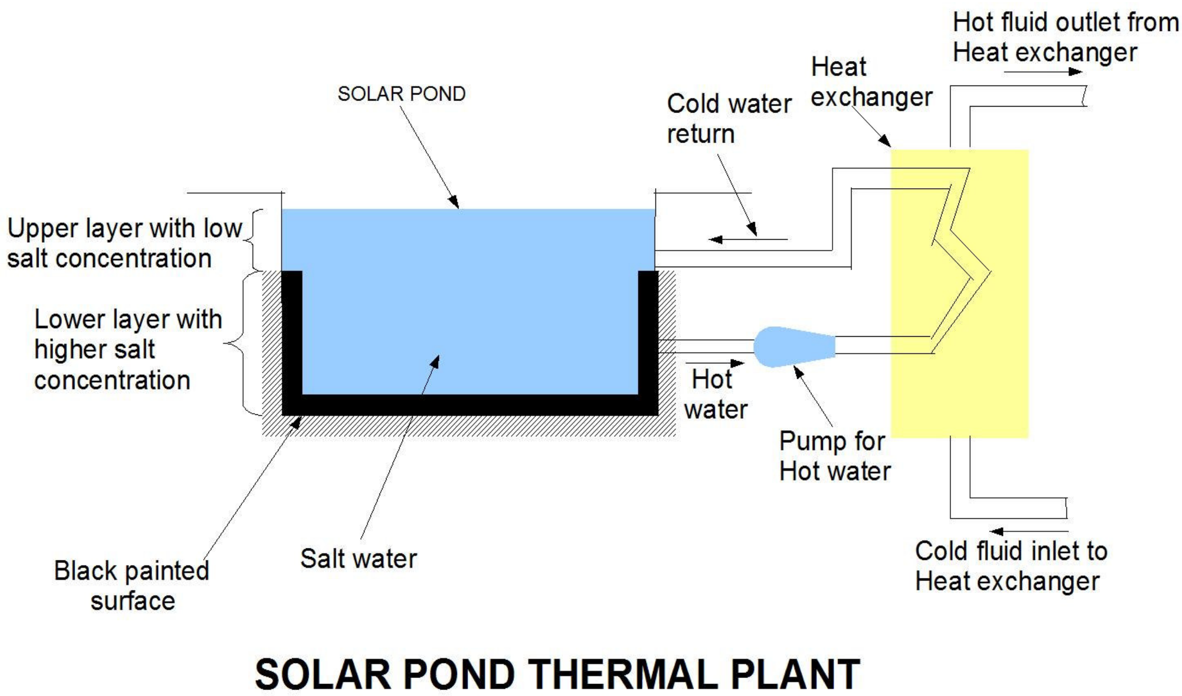


Figure 4: Solar pond thermal plant

Operation of solar pond:

Solar radiation passes through the upper layer to the bottom layer. The upper layer provides thermal insulation. Convection of water particles is prevented by the graded salt concentration and of higher density. Hence they remain at the bottom and get heated rapidly due to contact with black bottom.

Hot upper layer provides thermal insulation. In a well designed solar pond, the bottom layer temperature can reach up to 95^{O} C whereas the upper layer has the atmospheric temperature. The solar pond therefore acts like a thermal reservoir with large volume.

Applications of solar pond:

1. District heating,
2. Air conditioning;
3. Desalination plants;
4. Drying;
5. Water heating and
6. Electrical power generation.

Chapter 6

Gathering Power from Photovoltaic Power Sources

6.1: Introduction

The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy systems worldwide. Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators. The cost of renewable energy technologies is on a falling trend and is expected to fall further as demand and production increases. There are many renewable energy sources such as biomass, solar, wind, mini-hydro, and tidal power. One of the advantages offered by renewable energy sources is their potential to provide sustainable electricity in areas not served by the conventional power grid. The growing market for renewable energy technologies has resulted in a rapid growth in the need for power electronics. Most of the renewable energy technologies produce DC power, and hence power electronics and control equipment are required to convert the DC into AC power.

Inverters are used to convert DC to AC. There are two types of inverters: stand-alone and grid-connected. The two types have several similarities, but are different in terms of control functions. A stand-alone inverter is used in off-grid applications with battery storage. With backup diesel generators (such as PV–diesel hybrid power systems), the inverters may have additional control functions such as operating in parallel with diesel generators and bidirectional operation (battery charging and inverting). Grid-interactive inverters must follow the voltage and frequency characteristics of the utility-generated power presented on the distribution line. For both types of inverters, the conversion efficiency is a very important consideration. Details of stand-alone and grid-connected inverters for PV and wind applications are discussed in this chapter.

Section 6.2.5.2 covers stand-alone PV system applications such as battery charging and water pumping for remote areas. This section also discusses power electronic converters suitable for PV–diesel hybrid systems and grid-connected PV for rooftop and large-scale applications.

6.2 Basics of Photovoltaics

The density of power radiated from the sun (referred to as the ''solar energy constant'') at the outer atmosphere is 1.373kW/m^2. Part of this energy is absorbed and scattered by the earth's atmosphere. The final incident sunlight on earth's surface has a peak density of 1kW/m^2 at noon in the tropics. The technology of photovoltaics (PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity.

Solar cells rely on a quantum-mechanical process known as the ''photovoltaic effect'' to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode. Figure 1 shows a schematic diagram of the cross section through a crystalline solar cell [1]. It consists of a 0.2–0.3mm thick mono-crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ''doping'' it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (I_{ph}), which is internally generated in the solar cell, is proportional to the radiation intensity.

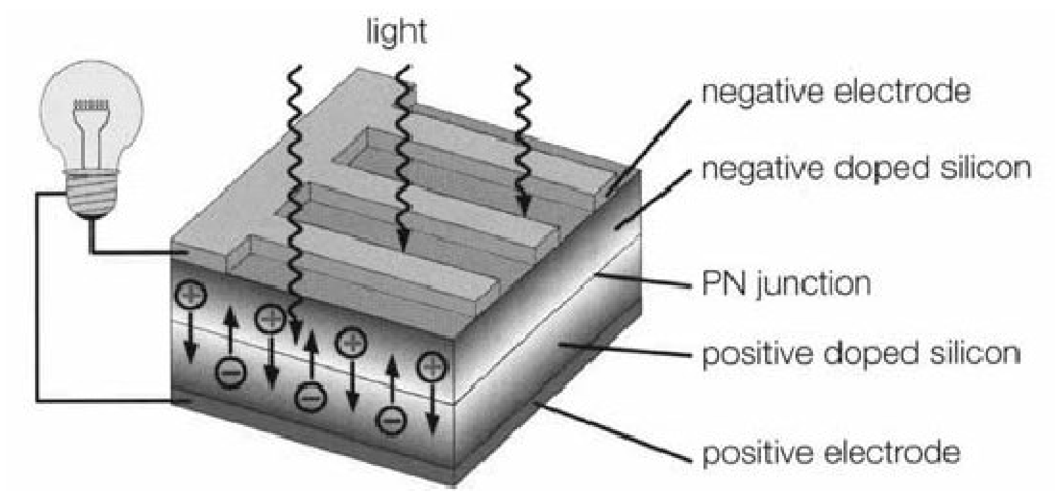


Figure 1: Solar Cell

A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Fig. 2a. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode are both zero. The entire photocurrent (Iph) generated by the solar radiation then flows to the output. The solar cell current has its maximum (Isc). If the load resistance is increased, which results in an increasing voltage across the p n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open-circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristic equation:

$$I = I_{ph} - I_0(e^{qV/kT} - l) = I_{ph} - I_d \tag{6.1}$$

where q is the electron charge, k is the Boltzmann constant, I_{ph} is photocurrent, I_0 is the reverse saturation current, Id is diode current, and T is the solar cell operating temperature (K). The current versus voltage (I-V) of a solar cell is thus equivalent to an ''inverted'' diode characteristic curve shown in Fig.2b.

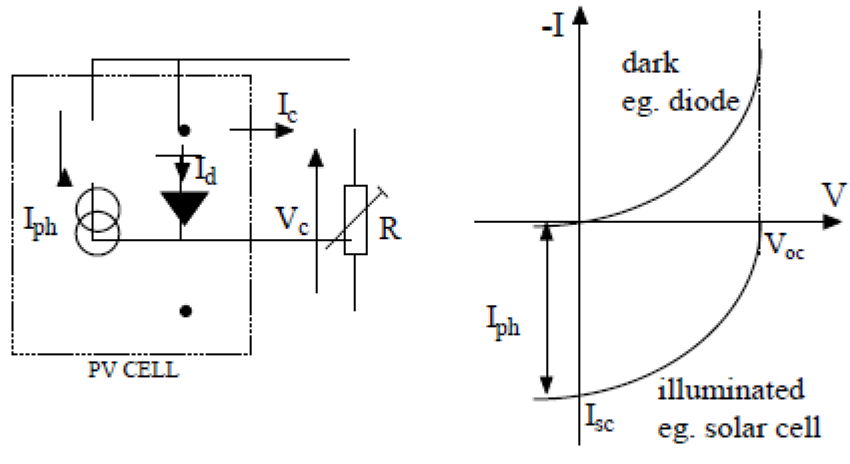


Figure 2: Equivalent circuit of a solar cell

A number of semiconductor materials are suitable for the manufacture of solar cells. The most common types using silicon semiconductor material (Si) are:

- Monocrystalline Si cells
- Polycrystalline Si cells
- Amorphous Si cells

A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Fig. 3. Two important points on this curve are the open circuit voltage (Voc) and short-circuit current (Isc). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, Voc is typically 0.6–0.7 V, and Isc is typically 20–40mA for every square centimeter of the cell area. To a good approximation, Isc is proportional to the illumination level, whereas Voc is proportional to the logarithm of the illumination level.

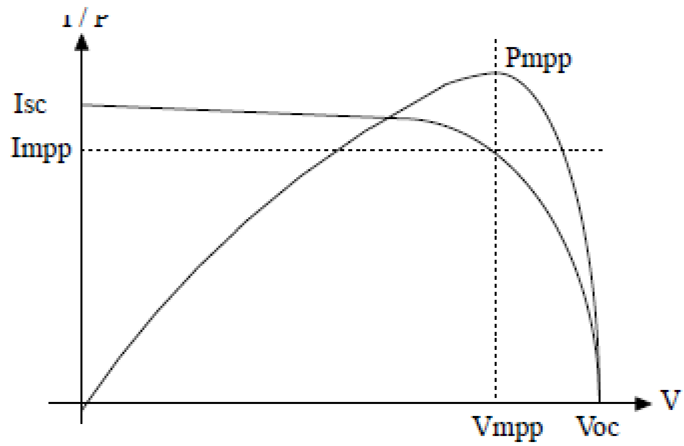


Figure 3: I vs. V characteristics of a solar cell

A plot of power (P) against voltage (V) for this device (Fig. 3) shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (Vmp, Imp). To maximize the power output, steps are usually taken during fabrication to maximize the three basic cell parameters: open-circuit voltage, short-circuit current, and fill factor (FF)—a term describing how ‘‘square’’ the I-V curve is, given by

$$\text{Fill Factor} = \frac{\text{Vmp Imp}}{\text{VocIsc}} \tag{6.2}$$

For a silicon solar cell, FF is typically 0.6–0.8.

Because silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Fig. 4).

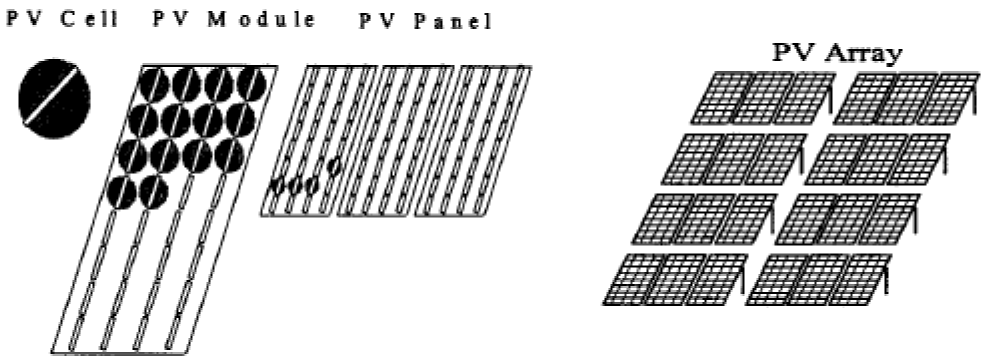


Figure 4: Elements of SPV system

The effect of temperature on the performance of a silicon solar module is illustrated in Fig. 6.5. Note that Isc slightly increases linearly with temperature, but Voc and the maximum power Pm decrease with temperature [1].

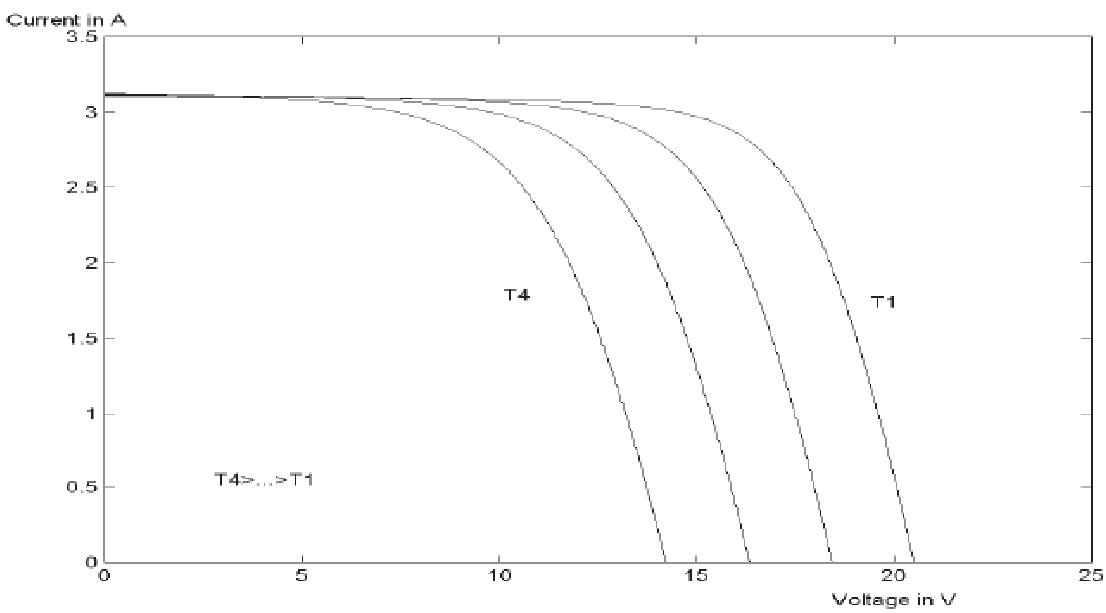


Figure 5: Effect of temperature on the performance of Silicon solar module

Figure 6 shows the variation of PV current and voltages at different insolation levels. From Figs. 5 and 6, it can be seen that the I V characteristics of solar cells at a given insolation and temperature consist of a constant-voltage segment and a constant-current segment [2]. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic where the two segments meet.

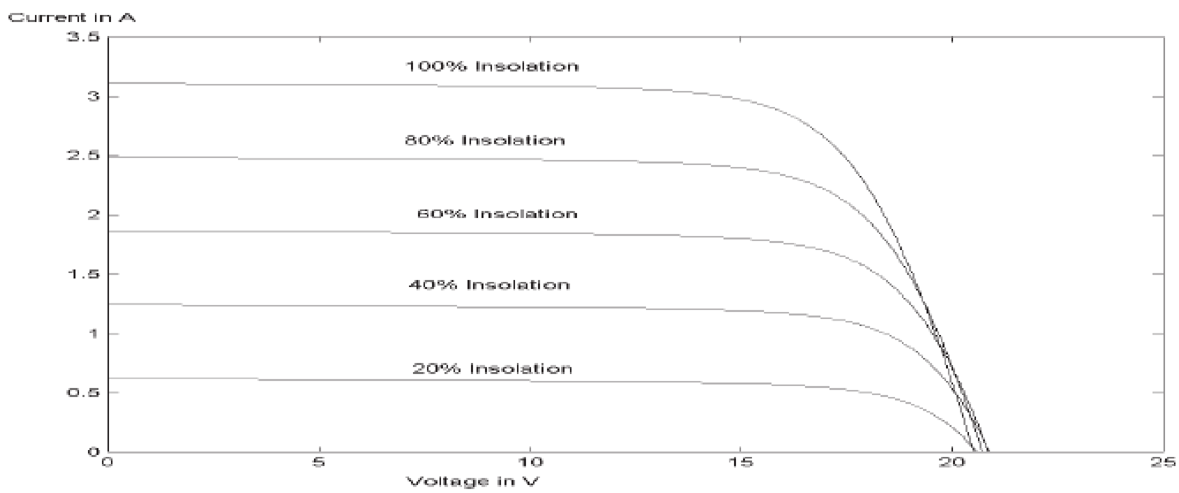


Figure 6: I-V characteristics for different insolation levels

6.3 Types of PV Power Systems

Photovoltaic power systems can be classified as follows:

- Stand-alone
- Hybrid
- Grid connected

Stand-alone PV systems, shown in Fig. 7a, are used in remote areas with no access to a utility grid. Conventional power systems used in remote areas often based on manually controlled diesel generators operating continuously or for a few hours. Extended operation of diesel generators at low load levels significantly increases maintenance costs and reduces their useful life. Renewable energy sources such as PV can be added to remote area power systems using diesel and other fossil fuel powered generators to provide 24-hour power economically and efficiently. Such systems are called ‘‘hybrid energy systems.’’ Figure 7b shows a schematic of a PV–diesel hybrid system. In grid-connected PV systems, as shown in Fig. 7c, PV panels are connected to a grid through inverters without battery storage. These systems can be classified as small systems, such as residential rooftop systems or large grid-connected systems. The grid interactive inverters must be synchronized with the grid in terms of voltage and frequency.

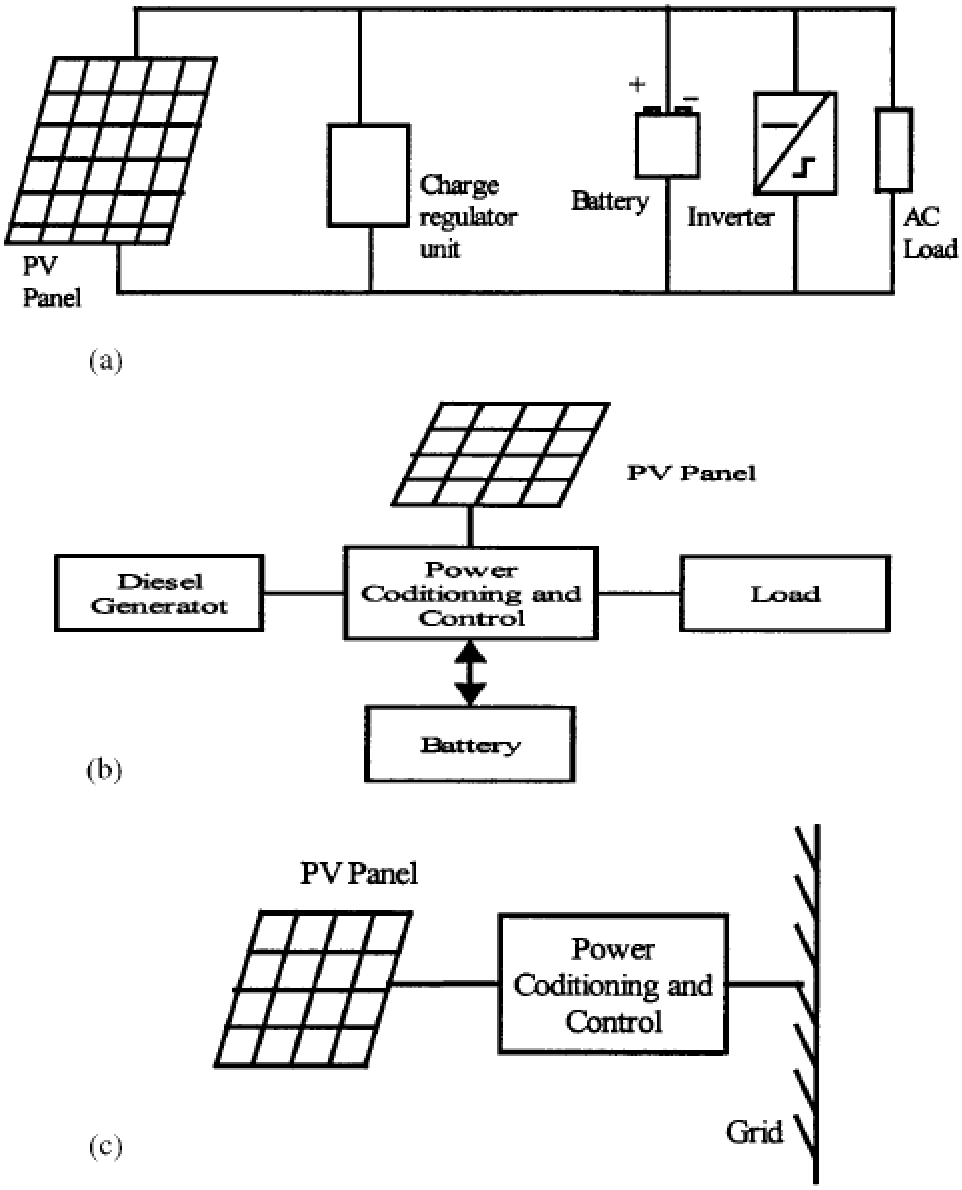


Figure 7: (a) Stand Alone PV system (b) PV-diesel hybrid system (c) Grid-connected PV system

6.4 Stand-Alone PV Systems

The two main stand-alone PV applications are:

- Battery charging
- Solar water pumping

6.4.1 Battery Charging

Batteries for PV Systems: A stand-alone photovoltaic energy system requires storage to meet the energy demand during periods of low solar irradiation and nighttime. Several types of batteries are available, such as lead-acid, nickel-cadmium, lithium, zinc bromide, zinc chloride, sodium–sulfur, nickel–hydrogen, red-ox and vanadium batteries. The provision of cost-effective electrical energy storage remains one of the major challenges for the development of improved PV power systems. Typically, lead-acid batteries are used to guarantee several hours to a few days of energy storage. Their reasonable cost and general availability has resulted in the widespread application of lead-acid batteries for remote area power supplies despite their limited lifetime compared to other system components. Lead acid batteries can be deep or shallow cycling, gelled batteries, batteries with captive or liquid electrolyte, sealed and non-sealed batteries, etc. [3]. Sealed batteries are valve regulated to permit evolution of excess hydrogen gas (although catalytic converters are used to convert as much evolved hydrogen and oxygen back to water as possible). Sealed batteries need less maintenance.

The following factors are considered in the selection of batteries for PV applications [1]:

- Deep discharge (70–80% depth discharge)

- Low charging/discharging current
- Long-duration charge (slow) and discharge (long duty cycle)
- Irregular and varying charge/discharge
- Low self-discharge
- Long lifetime
- Less maintenance requirement
- High energy storage efficiency
- Low cost

Battery manufacturers specify the nominal number of complete charge and discharge cycles as a function of the depth-of-discharge (DOD), as shown in Fig. 23.8. Although this information can be used reliably to predict the lifetime of lead-acid batteries in conventional applications, such as uninterruptable power supplies or electric vehicles, it usually results in an overestimation of the useful life of the battery bank in renewable energy systems.

Two of the main factors that have been identified as limiting criteria for the cycle life of batteries in photovoltaic power systems are incomplete charging and prolonged operation at a low state-of-charge (SOC). The objective of improved battery control strategies is to extend the lifetime of lead-acid batteries to achieve the typical number of cycles shown in Fig. 8. If this is achieved, an optimum solution for the required storage capacity and the maximum depth-of-discharge of the battery can be found by referring to the manufacturer's information.

Increasing the capacity will reduce the typical depth-of discharge and therefore prolong the battery lifetime. Conversely, it may be more economic to replace a smaller battery bank more frequently.

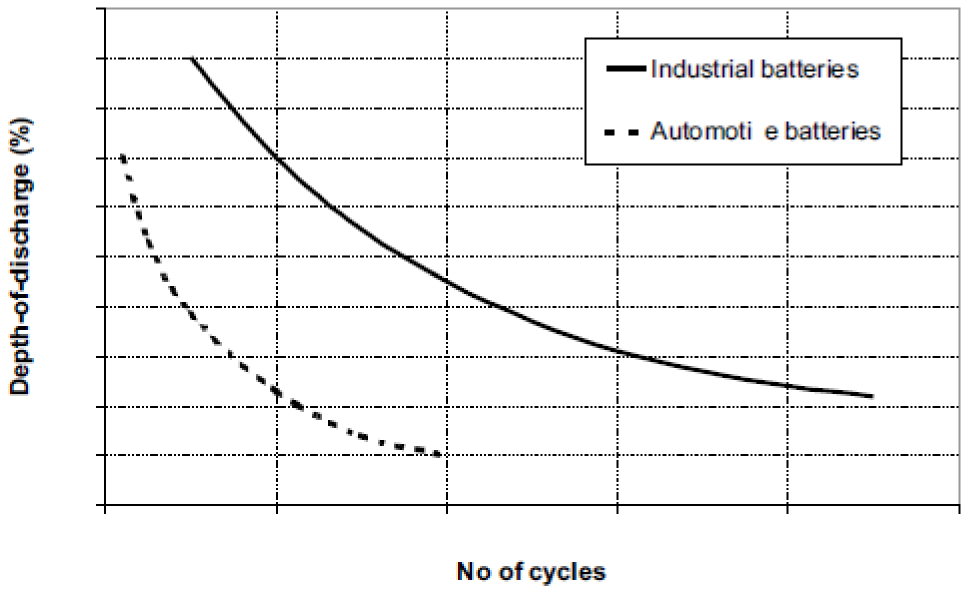


Figure 8: No. of battery cycles and Depth of discharge

PV Charge Controllers: Blocking diodes in series with PV modules are used to prevent the batteries from being discharged through the PV cells at night when there is no sun available to generate energy. These blocking diodes also protect the battery from short circuits. In a solar power system consisting of more than one string connected in parallel, if a short-circuit occurs in one of the strings, the blocking diode prevents the other PV strings from discharging through the short-circuited string. The battery storage in a PV system should be properly controlled to avoid catastrophic operating conditions like overcharging or frequent deep discharging. Storage batteries account for most PV system failures and contribute significantly to both the initial and the eventual replacement costs. Charge controllers regulate the charge transfer and prevent the battery from being excessively charged and discharged.

Three types of charge controllers are commonly used:

- Series charge regulators
- Shunt charge regulators
- DC–DC Converters

Series Charge Regulators: The basic circuit for the series regulators is given in Fig. 9. In the series charge controller, the switch S1 disconnects the PV generator when a predefined battery voltage is achieved. When the voltage falls below the discharge limit, the load is disconnected from the battery to avoid deep discharge beyond the limit. The main problem associated with this type of controller is the losses associated with the switches. This extra power loss has to come from the PV power, and this can be quite significant. Bipolar transistors, MOSFETs, or relays are used as the switches.

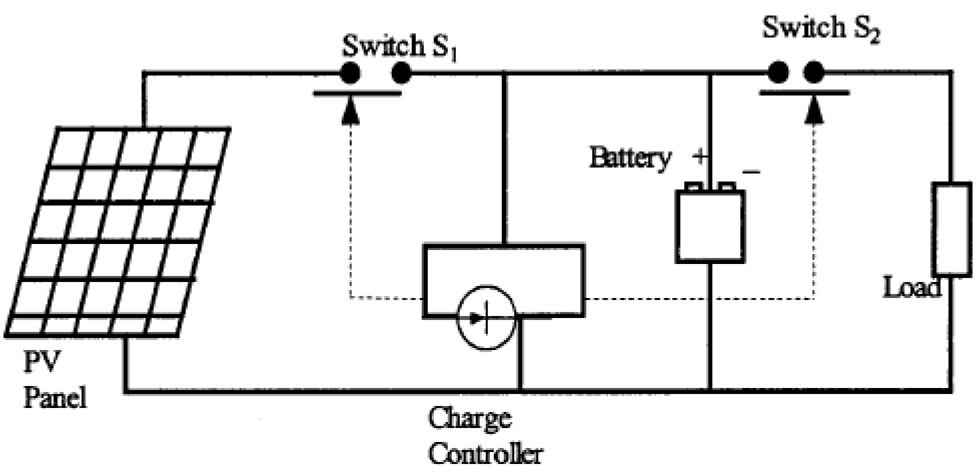


Figure 9: Series Charge Regulator

Shunt Charge Regulators: In this type, as illustrated in Fig.10, when the battery is fully charged the PV generator is short-circuited using an electronic switch (S1). Unlike series controllers, this method works more efficiently even when the battery is completely discharged, as the short circuit switch need not be activated until the battery is fully discharged [1]. The blocking diode prevents short-circuiting of the battery.

Shunt charge regulators are used for small PV applications (less than 20 A). Deep-discharge protection is used to protect the battery against deep discharge. When the battery voltage reaches below the minimum set point for the deep-discharge limit, switch S2 disconnects the load. Simple series and shunt regulators allow only relatively coarse adjustment of the current flow and seldom meet the exact requirements of PV systems.

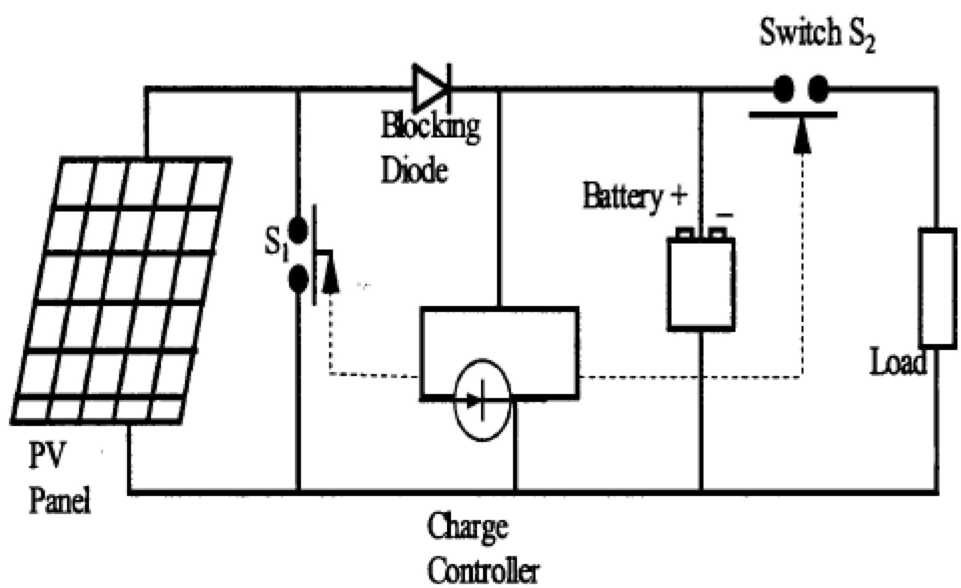


Figure 10: Shunt Charge Regulators

DC–DC Converter Type Charge Regulators: Switch mode DC-to-DC converters are used to match the output of a PV generator to a variable load. There are various types of DC–DC converters:

- Buck (step-down) converter
- Boost (step-up) converter

- Buck-boost (step-down/up) converter

Figures 11a, 11b, and 11c show simplified diagrams of these three basic types of converters. The basic concepts are an electronic switch, an inductor to store energy, and a ‘‘flywheel’’ diode, which carries the current during that part of switching cycle when the switch is off. The DC–DC converters allow the charge current to be reduced continuously in such a way that the resulting battery voltage is maintained at a specified value.

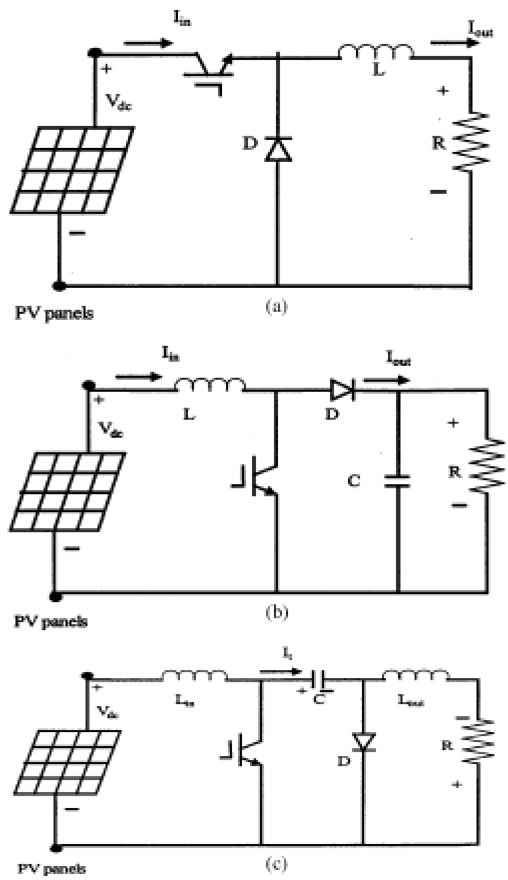


Figure 11: (a) Buck Converter (b) Boost Converter (c) Buck-Boost Converter

6.4.2 Solar Water Pumping

In many remote and rural areas, hand pumps or diesel driven pumps are used for water supply. Diesel pumps consume fossil fuel, affect the environment, need more maintenance, and are less reliable. Photovoltaic (PV)-powered water pumps have received considerable attention because of major developments in the field of solar-cell materials and power electronic systems technology.

Types of Pumps: Two types of pumps are commonly used for water-pumping applications: Positive displacement and centrifugal. Both centrifugal and positive displacement pumps can be further classified into those with motors that are surface mounted, and those that are submerged into the water (‘‘submersible’’).

Displacement pumps have water output directly proportional to the speed of the pump, but almost independent of head. These pumps are used for solar water pumping from deep wells or bores. They may be piston-type pumps or use a diaphragm driven by a cam or rotary screw, or use a progressive cavity system. The pumping rate of these pumps is directly related to the speed, and hence constant torque is desired.

Centrifugal pumps are used for low-head applications, especially if they are directly interfaced with the solar panels. Centrifugal pumps are designed for fixed-head applications, and the pressure difference generated increases in relation to the speed of the pump. These pumps are of the rotating impeller type, which throws the water radially against a casing shaped so that the momentum of the water is converted into useful pressure for lifting [3]. The centrifugal pumps have relatively high efficiency, but it decreases at lower speeds, which can be a problem for a solar water-pumping system at times of low light levels. The single-stage centrifugal pump has just one impeller, whereas most borehole pumps are multistage types where the outlet from one impeller goes into the center of another and each one keeps increasing the pressure difference. From Fig. 12a, it is quite obvious that the load line is located far away from the P_{max} line. It has been reported that the daily utilization efficiency for a DC motor drive is 87% for a centrifugal pump compared to 57% for a constant-torque characteristic load. Hence, centrifugal pumps are more compatible with PV arrays. The system operating point is determined by the intersection of the I V characteristic of the PV array and that of the motor, as shown in Fig. 12a. The torque-speed slope is normally large because of the armature resistance being small. At the instant of starting, the speed and the back emf are zero. Hence the motor starting current is approximately the short-circuit current of the PV array. Matching the load to the PV source through a maximum power-point tracker increases the starting torque.

The matching of a DC motor depends on the type of load being used. For instance, a centrifugal pump is characterized by having the load torque proportional to the square of speed. The operating characteristics of the system (i.e., PV source, PM DC motor, and load) are at the intersection of the motor and load characteristics as shown in Fig. 12b (i.e., points a; b; c; d; e, and f for the centrifugal pump). From Fig. 12b, the system utilizing the centrifugal pump as its load tends to start at low solar irradiation (point a) level. However, for systems with an almost constant torque characteristic (Fig.12(b), line 1), the start is at almost 50% of one sun (full insolation), which results in a short period of operation.

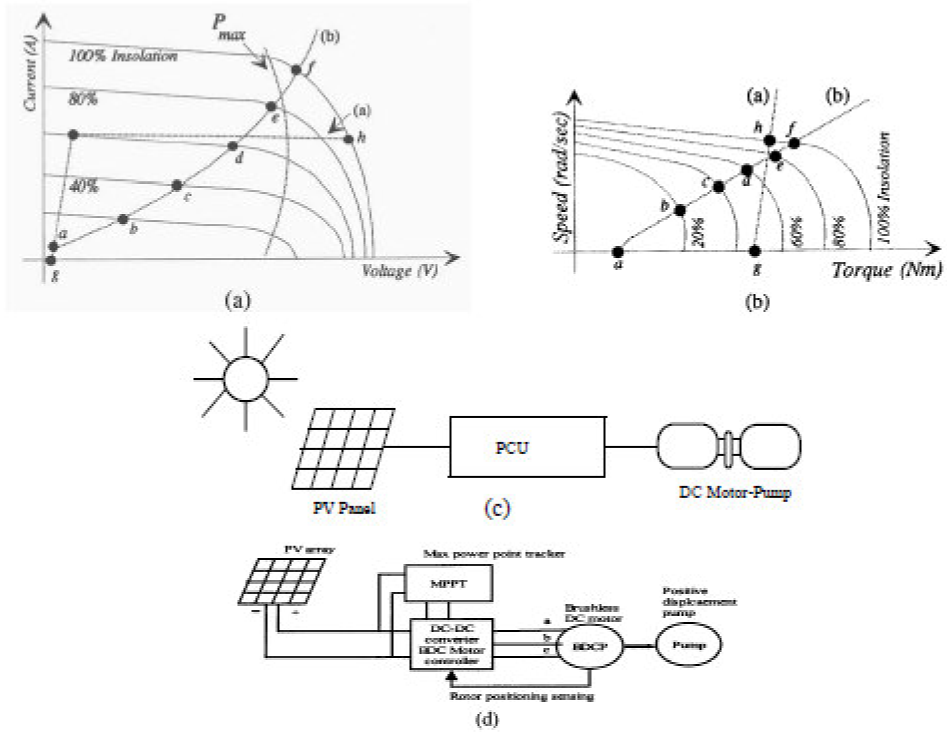


Figure 12: I-V Characteristics of PV array and two mechanical loads (b) Speed Torque characteristics of DC motor and two mechanical loads (c) Block diagram for DC motor driven pumping scheme (d) Block diagram for brushless DC motor for PV application

Types of Motors: There are various types of motors available for the PV water pumping applications: DC motors and AC motors. DC motors are preferred where direct coupling to photovoltaic panels is desired, whereas AC motors are coupled to the solar panels through inverters. AC motors in general are cheaper than DC motors and are more reliable, but DC motors are more efficient. The DC motors used for solar pumping applications are permanent-magnet DC motors with or without brushes.

In DC motors with brushes, the brushes are used to deliver power to the commutator and need frequent replacement because of wear and tear. These motors are not suitable for submersible applications unless long transmission shafts are used. Brushless DC permanent-magnet motors have been developed for submersible applications. The AC motors are of the induction motor type, which is cheaper than DC motors and available worldwide. However, they need inverters to change DC input from the PV to AC power. A comparison of the different types of motors used for PV water pumping is given in Table 1.

Table 1: Comparison of different types of motors

Types of Motor	Advantages	Disadvantages	Main Features
Brushed dc	• Simple and efficient for PV applications • No complex control circuit is required, as the motor starts without high current surge; these motors will run slowly but do not overheat with reduced voltage	• Brushes need to be replaced periodically (typical replacement interval is 2000 to 4000 h or 2 years) • Available only in small motor sizes	• Requires maximum power point tracker for optimum performance • Available only in small motor sizes • Increasing current (by paralleling PV modules) increases the torque; increasing voltage (by series PV modules) increases the speed
Brushless dc	• Efficient • Less maintenance is required	• Electronic computation adds to extra cost, complexity, and increased risk of failure/malfunction • In most cases, oil cooled, cannot be submerged as deeply as water-cooled ac units	• Growing trend among PV pump manufacturers to use brushless dc motors, primarily for centrifugal-type submersible pumps
Ac induction motors	• No brushes to replace • Can use existing ac motor/pump technology, which is cheaper and easily available worldwide; these motors can handle larger pumping requirements	• Needs an inverter to convert DC output from PV to AC, adding cost and complexity • Less efficient than dc motor-pump units • Prone to overheating if current is not adequate to start the motor or if the voltage is too low	• Available for single or three supply • Inverters are designed to regulate frequency to maximize power to the motor in response to changing insolation levels

Power Conditioning Units for PV Water Pumping: Most PV pump manufacturers include power conditioning units (PCUs), which are used for operating the PV panels close to their maximum power point over a range of load conditions and varying insolation levels, and also for power conversion. DC or AC motor pump units can be used for PV water pumping. In its simplest from, a solar water pumping system comprises of PV array, PCU and DC water pump unit as shown in Figure 12(c). In case of lower light levels, high currents can be generated through power conditioning to help in starting the motor pump units, especially for reciprocating positive-displacement type pumps with constant torque characteristics requiring constant current throughout the operating region. In positive- displacement type pumps, the torque generated by the pumps depends on the pumping head, friction, pipe diameter, etc., and requires a certain level of current to produce the necessary torque. Some systems use electronic controllers to assist in starting and operating the motor under low solar radiation. This is particularly important when using positive displacement pumps. The solar panels generate DC voltage and current. Solar water pumping systems usually have DC or AC pumps. For DC pumps, the PV output can be directly connected to the pump through maximum power point tracker, or a DC–DC converter can also be used for interfacing for controlled DC output from PV panels. To feed the ac motors, a suitable interface is required for the power conditioning. These PV inverters for the stand-alone applications are very expensive. The aim of power conditioning equipment is to supply the controlled voltage/current output from the converters/inverters to the motor-pump unit.

These power-conditioning units are also used for operating the PV panels close to their maximum efficiency for fluctuating solar conditions. The speed of the pump is governed by the available driving voltage. If current becomes lower than the acceptable limit, then the pumping will stop. When the light level increases, the operating point will shift from the maximum-power point leading to a reduction in efficiency. For centrifugal pumps, there is an increase in current at increased speed, and the matching of I V characteristics is closer for a wide range of light intensity levels. For centrifugal pumps, the torque is proportional to the square of the speed, and the torque produced by the motors is proportional to the current. Because of the decrease in PV current output, the torque from the motor and consequently the speed of the pump are reduced, resulting in a decrease in back emf and the required voltage for the motor. A maximum-power-point tracker (MPPT) can be used for controlling the voltage=current outputs from the PV inverters to operate the PV close to the maximum operating point for smooth operation of motorpump units. The DC–DC converter can be used to keep the PVpanel output voltage constant and to help in operating the solar arrays close to the maximum-power point. In the beginning, a high starting current is required to produce a high starting torque. The PV panels cannot supply this high starting current without adequate power conditioning equipment such as a DC–DC converter or by using a starting capacitor. The DC–DC converter can generate the high starting currents by regulating the excess PV array voltage. The DC–DC converter can be a boost or buck converter.

Brushless DC motors (BDCM) and helical rotor pumps can also be used for PV water pumping [20]. BDCMs are a self-synchronous type of motor characterized by trapezoidal waveforms for back emf and air flux density. They can operate off a low-voltage DC supply that is switched through an inverter to create a rotating stator field. The current generation of BDCMs use rare earth magnets on the rotor to give high airgap flux densities and are well suited to solar application. The block diagram of such an arrangement, shown in Fig. 12d, consists of PV panels, a DC–DC converter, an MPPT, and a brushless DC motor.

The PV inverters are used to convert the DC output of the solar arrays to an AC quantity so as to run the ac motor-driven pumps. These PV inverters can be of the variable-frequency type, which can be controlled to operate the motors over a wide range of loads. The PV inverters may involve impedance matching to match the electrical characteristics of the load and array. The motor–pump unit and PV panels operate at their maximum efficiencies [7]. The MPPT is also used in the power conditioning. To keep the voltage stable for the inverters, the DC–DC converter can be used. The inverter/converter has the capability of injecting high-switch-frequency components, which can lead to overheating and losses, care must be taken in doing this. The PV arrays are usually connected in series, parallel, or a combination of series and parallel configurations.

The function of power electronic interface, as mentioned before, is to convert the DC power from the array to the required voltage and frequency to drive the AC motors. The motor–pump system load should be such that the array operates close to its maximum power point at all solar insolation levels. There are mainly three types solar powered water pumping systems, as shown in Fig. 13.

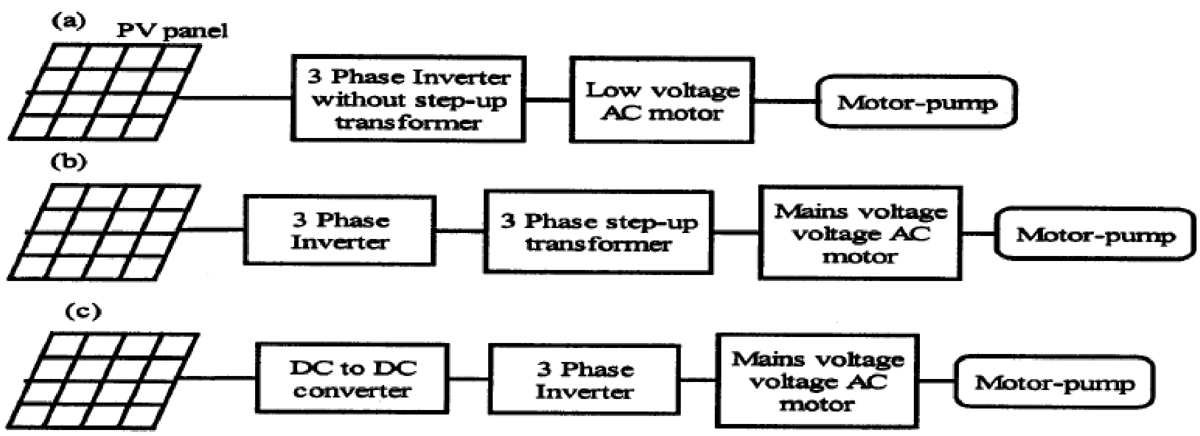


Figure 13: Block diagram for AC motor driven pumping schemes

The first system shown in Fig 13a is an imported commercially available unit, which uses a specially wound low-voltage induction-motor-driven submersible pump. Such a low-voltage motor permits the PV array voltage to be converted to AC without using a step-up transformer. The second system, shown in Fig. 13b, makes use of a conventional ‘‘off-the-shelf ’’ 415-V, 50-Hz, induction motor [6]. This scheme needs a step-up transformer to raise inverter output voltages to high voltage. The third scheme as shown in Fig. 13c comprises of a DC-to-DC converter, an inverter that switches at high frequency, and a mains-voltage motor-driven pump. To get the optimum discharge (Q) at a given insolation level, the efficiency of the DC–DC converter and the inverter should be high. So the purpose should be to optimize the output from the PV array, motor, and pump. The principle used here is to vary the duty cycle of a DC-to-DC converter so that the output voltage is maximum. The DC-to-DC converter is used to boost the solar array voltage to eliminate the need for a step-up transformer and to operate the array at the maximum power point. The three-phase inverter used in the interface is designed to operate in a variable-frequency mode over the range of 20 to 50-Hz, which is the practical limit for most 50-Hz induction motor applications. The block diagram for frequency control is given in Fig. 14. This inverter would be suitable for driving permanent-magnet motors by incorporating additional circuitry for position sensing of the motor’s shaft. Also, the inverter could be modified, if required, to produce higher output frequencies for high-speed permanent-magnet motors. The inverter has a three-phase full-bridge configuration implemented by MOSFET power transistors.

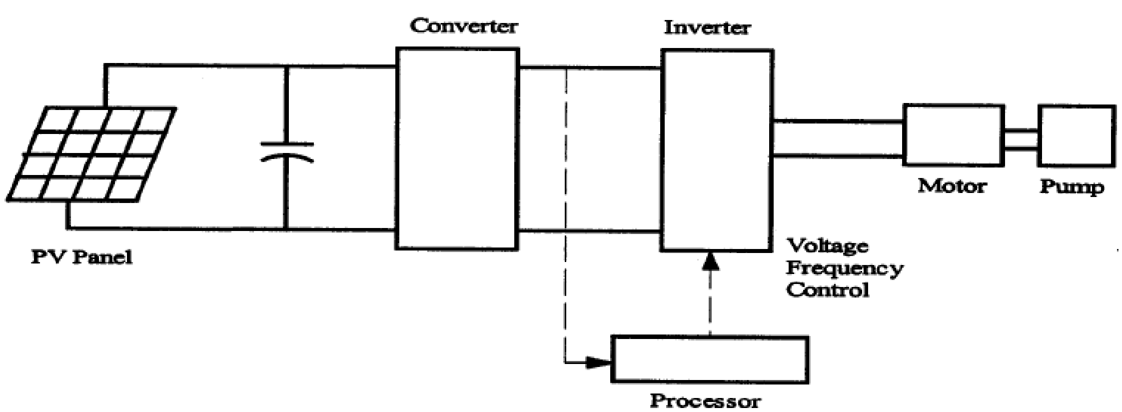


Figure 14: Block diagram for V/f control

6.5 PV–Diesel Systems (Hybrid)

Photovoltaic–diesel hybrid energy systems generate AC electricity by combining a photovoltaic array with an inverter, which can operate alternately or in parallel with a conventional engine-driven generator. They can be classified according to their configuration as follows [8]:

1. Series hybrid energy systems

2. Switched hybrid energy systems

3. Parallel hybrid energy systems

An overview of the three most common system topologies is presented by Bower [9]. In the following comparison, typical PV–diesel system configurations are described.

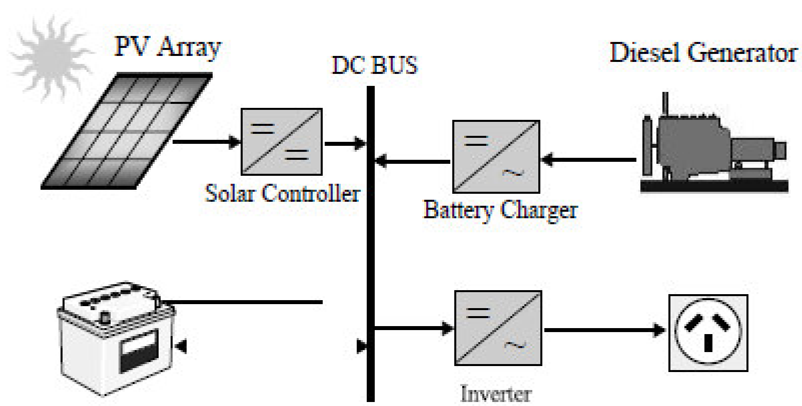


Figure 15: Series Connection

Series Configuration: Figure 15 shows a series PV–diesel hybrid energy system. To ensure reliable operation of series hybrid energy systems, both the diesel generator and the inverter have to be sized to meet peak loads. This results in a typical system operation where a large fraction of the generated energy is passed through the battery bank, resulting in increased cycling of the battery bank and reduced system efficiency. AC power delivered to the load is converted from DC to regulated AC by an inverter or a motor generator unit. The power generated by the diesel generator is first rectified and subsequently converted back to AC before being supplied to the load, which leads to significant conversion losses.

The actual load demand determines the amount of electrical power delivered by the photovoltaic array, the battery bank, or the diesel generator. The solar controller prevents overcharging of the battery bank from the PV generator when the PV power exceeds the load demand and the batteries are fully charged. It may include maximum power point tracking to improve the utilization of the available photovoltaic energy, although the energy gain is marginal for a well-sized system. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven generator.

The advantages of such a system include the following:

1. The engine-driven generator can be sized to be optimally loaded while supplying the load and charging the battery bank, until a battery state-of-charge (SOC) of 70–80% is reached.
2. No switching of AC power between the different energy sources is required, which simplifies the electrical output interface.
3. The power supplied to the load is not interrupted when the diesel generator is started.
4. The inverter can generate a sine-wave, modified square wave, or square wave, depending on the application.

The disadvantages are:

1. The inverter cannot operate in parallel with the engine driven generator; therefore, the inverter must be sized to supply the peak load of the system.
2. The battery bank is cycled frequently, which shortens its lifetime.
3. The cycling profile requires a large battery bank to limit the depth-of-discharge.
4. The overall system efficiency is low, since the diesel cannot supply power directly to the load;
5. Inverter failure results in complete loss of power to the load, unless the load can be supplied directly from the diesel generator for emergency purposes.

Switched Configuration: Despite its operational limitations, the switched configuration as shown in Fig. 16 remains one of the most common installations today. It allows operation with either the engine driven generator or the inverter as the AC source, yet no parallel operation of the main generation sources is possible. The diesel generator and the renewable energy source can charge the battery bank. The main advantage compared with the series system is that the load can be supplied directly by the engine-driven generator, which results in a higher overall conversion efficiency. Typically, the diesel generator power will exceed the load demand, with excess energy being used to recharge the battery bank. During periods of low electricity demand the diesel generator is switched off and the load is supplied from the PV array together with stored energy.

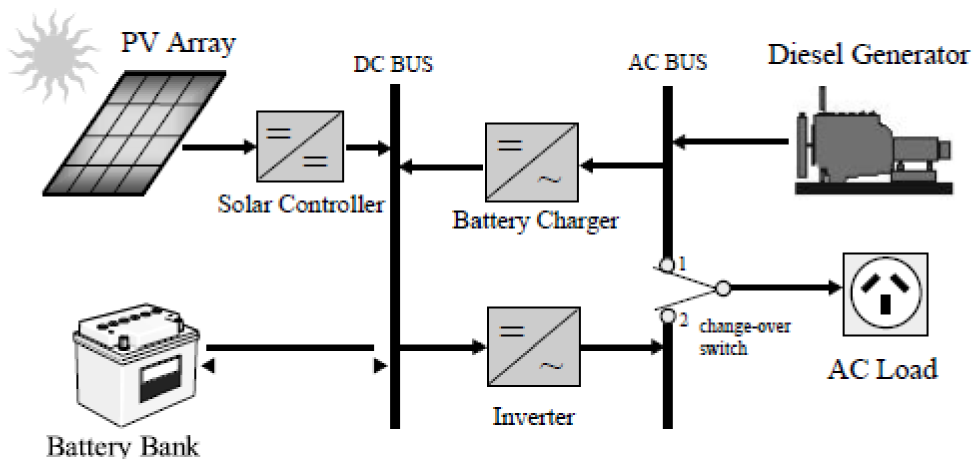


Figure 16: Switched PV-Diesel hybrid energy system

Switched hybrid energy systems can be operated in manual mode, although the increased complexity of the system makes it highly desirable to include an automatic controller, which can be implemented with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven generator.

The advantages of this system are:

1. The inverter can generate a sine-wave, modified square wave, or square wave, depending on the particular application.
2. The diesel generator can supply the load directly, therefore improving the system efficiency and reducing the fuel consumption.

The disadvantages are:

1. Power to the load is interrupted momentarily when the AC power sources are transferred.
2. The engine-driven alternator and inverter are typically designed to supply the peak load, which reduces their efficiency at part-load operation.

Parallel Configuration: The parallel configuration shown in Fig. 17 allows all energy sources to supply the load separately at low or medium load demand, as well as supplying peak loads from combined sources by synchronizing the inverter with the alternator output waveform. The bidirectional inverter can charge the battery bank (rectifier operation) when excess energy is available from the engine-driven generator, as well as act as a DC–AC converter (inverter operation). The bidirectional inverter may provide ‘‘peak shaving’’ as part of the control strategy when the engine-driven generator is overloaded.

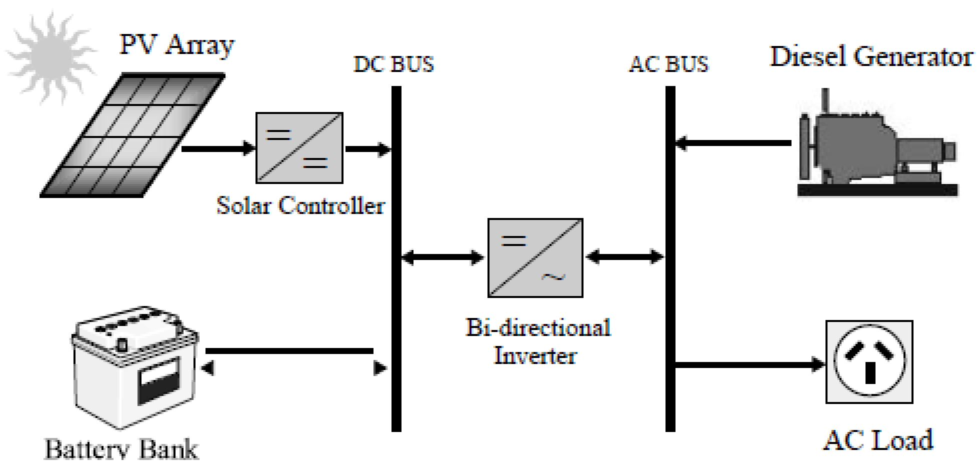


Figure 17: Parallel PV-Diesel hybrid energy system

Parallel hybrid energy systems are characterized by two significant improvements over the series and switched system configurations.

1. The inverter plus the diesel generator capacity rather than their individual component ratings limit the maximum load that can be supplied. Typically, this will lead to a doubling of the system capacity. The capability to synchronize the inverter with the diesel generator allows greater flexibility to optimize the operation of the system. Future systems should be sized with a reduced

peak capacity of the diesel generator, which results in a higher fraction of directly used energy and hence higher system efficiencies.

2. By using the same power electronic devices for both inverter and rectifier operation, the number of system components is minimized. Additionally, wiring and system installation costs are reduced through the integration of all power conditioning devices in one central power unit. This highly integrated system concept has advantages over a more modular approach to system design, but it may prevent convenient system upgrades when the load demand increases.

The parallel configuration offers a number of potential advantages over other system configurations. These objectives can only be met if the interactive operation of the individual components is controlled by an ''intelligent'' hybrid energy management system. Although today's generation of parallel systems includes system controllers of varying complexity and sophistication, they do not optimize the performance of the complete system. Typically, both the diesel generator and the inverter are sized to supply anticipated peak loads. As a result, most parallel hybrid energy systems do not utilize their capability of parallel, synchronized operation of multiple power sources.

The advantages of this system include the following:

1. The system load can be met in an optimal way.
2. Diesel generator efficiency can be maximized.
3. Diesel generator maintenance can be minimized.
4. A reduction in the rated capacities of the diesel generator, battery bank, inverter, and renewable resources is feasible, while also meeting the peak loads.

The disadvantages are:

1. Automatic control is essential for the reliable operation of the system.
2. The inverter has to be a true sine-wave inverter with the ability to synchronize with a secondary AC source.
3. System operation is less transparent to the untrained user of the system.

6.6 Control of PV–Diesel Hybrid Systems

The design process of hybrid energy systems requires the selection of the most suitable combination of energy sources, power-conditioning devices, and energy-storage system, together with the implementation of an efficient energy dispatch strategy. System simulation software is an essential tool to analyze and compare possible system combinations. The objective of the control strategy is to achieve optimal operational performance at the system level. Inefficient operation of the diesel generator and ‘‘dumping’’ of excess energy is common for many remote-area power supplies operating in the field. Component maintenance and replacement contributes significantly to the life-cycle cost of systems. These aspects of system operation are clearly related to the selected control strategy and have to be considered in the system design phase.

Advanced system control strategies seek to reduce the number of cycles and the depth-of-discharge for the battery bank, run the diesel generator in its most efficient operating range, maximize the utilization of the renewable resource, and ensure high reliability of the system. Because of the varying nature of the load demand, the fluctuating power supplied by the photovoltaic generator, and the resulting variation of battery SOC, the hybrid energy system controller has to respond to continuously changing operating conditions.

Figure 18 shows different operating modes for a PV single-diesel system using a typical diesel dispatch strategy.

Mode (I): The base load, which is typically experienced at night and during the early morning hours, is supplied by energy stored in the batteries. Photovoltaic power is not available and the diesel generator is not started.

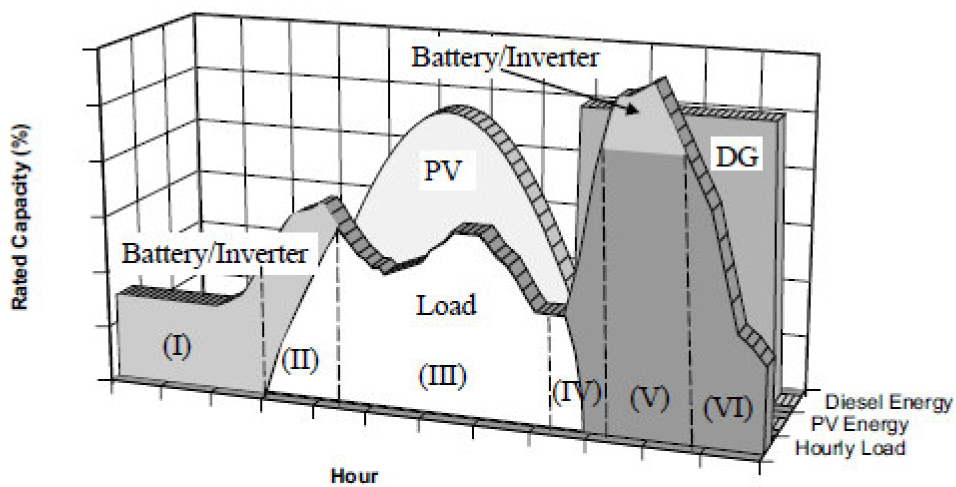


Figure 18: Operating modes of PV Diesel hybrid energy system

Mode (II): PV power is supplemented by stored energy to meet the medium load demand.

Mode (III): Excess energy is available from the PV generator, which is stored in the battery. The medium load demand is supplied from the PV generator.

Mode (IV): The diesel generator is started and operated at its nominal power to meet the high evening load. Excess energy available from the diesel generator is used to recharge the batteries.

Mode (V): The diesel generator power is insufficient to meet the peak load demand. Additional power is supplied from the batteries by synchronizing the inverter AC output voltage with the alternator waveform.

Mode (VI): The diesel generator power exceeds the load demand, but it is kept operational until the batteries are recharged to a high state-of-charge level.

In principle, most efficient operation is achieved if the generated power is supplied directly to the load from all energy sources, which also reduces cycling of the battery bank. However, since diesel generator operation at light loads is inherently inefficient, it is common practice to operate the engine-driven generator at its nominal power rating and to recharge the batteries from the excess energy. The selection of the most efficient control strategy depends on fuel, maintenance and component-replacement cost, the system configuration, and environmental conditions, as well as constraints imposed on the operation of the hybrid energy system.

6.7 Grid Connected PV Systems

Utility interactive inverters not only condition the power output of the photovoltaic arrays but ensure that the PV system output is fully synchronized with the utility power. These systems can be battery-less or with battery backup. Systems with battery storage (or a flywheel) provide additional power-supply reliability. The grid connection of photovoltaic systems is gathering momentum because of various rebate and incentive schemes. This system allows the consumer to feed its own load utilizing the available solar energy, and the surplus energy can be injected into the grid under the energy buy-back scheme to reduce the payback period. Grid-connected PV systems can become a part of the utility system. The contribution of solar power depends on the size of system and the load curve of the house. When the PV system is integrated with the utility grid, a two-way power flow is established. The utility grid will absorb excess PV power and will feed the house at night and at instants when the PV power is inadequate. The utility companies are encouraging this scheme in many parts of the world. The grid-connected system can be classified as follows:

- Rooftop application of grid-connected PV system
- Utility-scale large system

For small household PV applications, a roof-mounted PV array can be the best option. Solar cells provide an environmentally clean way of producing electricity, and rooftops have always been the ideal place to put them. With a PV array on the rooftop, the solar-generated power can supply residential load. The rooftop PV systems can help in reducing the peak summer load to the benefit of utility companies by feeding the household lighting, cooling, and other domestic loads. The battery storage can further improve the reliability of the system at times of low insolation level, at night or on cloudy days. But the battery storage has some inherent problems, such as maintenance and higher cost. For roof-integrated applications, the solar arrays can be either mounted on the roof or directly integrated into the roof. If the roof integration does not allow for an air channel behind the PV modules for ventilation purposes, then it can increase the cell temperature during the operation, consequently leading to some energy losses. The disadvantage of the rooftop application is that the PV array orientation is dictated by the roof. In cases, where the roof orientation differs from the optimal orientation required for the cells, the efficiency of the entire system would be suboptimal.

Utility interest in PV has centered on the large grid connected PV systems. In Germany, the United States, Spain, and several other parts of the world, some large PV-scale plants have been installed. The utilities are more inclined toward large-scale, centralized power supplies. The PV systems can be centralized or distributed systems.

Grid-connected PV systems must observe the islanding situation, when the utility supply fails. In case of islanding, the PV generators should be disconnected from mains. PV generators can continue to meet only the local load, if the PV output matches the load. If the grid is reconnected during islanding, transient over-currents can flow through the PV system inverters, and protective equipment such as circuit breakers may be damaged. Islanding control can be achieved through inverters or via the distribution network. Inverter controls can be designed on the basis of detection of grid voltage or measurement of impedance, frequency variation, or increase in harmonics. Protection must be designed for islanding, short circuits, over=under voltages/currents, grounding and lightning etc.

The importance of the power generated by the PV system depends on the time of the day, especially when the utility is experiencing peak load. The PV plants are well suited to summer peaking, but it depends upon the climatic condition of the site. PV systems being investigated for use as peaking stations would be competitive for load management. The PV users can defer their load by adopting load management to get the maximum benefit out of the grid-connected PV plants and feeding more power into the grid at the time of peak load.

The assigned capacity credit is based on the statistical probability that the grid can meet peak demand [3]. The capacity factor during peaks is very similar to that of conventional plants, and similar capacity credit can be given for PV generation, except at times when the PV plants are generating very much less power, unless adequate storage is provided.

With the installation of PV plants, the need for extra transmission lines and transformers can be delayed or avoided. The distributed PV plants can also contribute in providing reactive power support to the grid and reduce the burden on VAR compensators.

6.7.1 Inverters for Grid-Connected Applications

The power conditioner is the key link between the PV array and mains in the grid-connected PV system. It acts as an interface that converts DC current produced by the solar cells into utility-grade AC current. The PV system behavior relies heavily on the power-conditioning unit. The inverters must produce good-quality sine-wave output, must follow the frequency and voltage of the grid, and must extract maximum power from the solar cells with the help of a maximum-power point tracker. The inverter input stage varies the input voltage until the maximum power point on the I V curve is found. The inverter must monitor all the phases of the grid, and inverter output must be controlled in terms of voltage and frequency variation. A typical grid-connected inverter may use a pulse-width modulation (PWM) scheme and operate in the range of 2 kHz up to 20 kHz.

6.7.2 Inverter Classifications

The inverters used for grid interfacing are broadly classified as voltage-source inverters (VSI) and current-source inverters (CSI); whereas the inverters based on the control schemes can be classified as current-controlled inverters (CCI) and voltage-controlled inverters (VCI). The source is not necessarily characterized by the energy source for the system. It is a characteristic of the topology of the inverter. It is possible to change from one source type to another source type by the addition of passive components. In the voltage-source inverter (VSI), the DC side is made to appear to the inverter as a voltage source. The voltage-source inverters have a capacitor in parallel across the input, whereas the current-source inverters have an inductor in series with the DC input. In the current source inverter (CSI), the DC source appears as a current source to the inverter. Solar arrays are fairly good approximation to a current source. Most PV inverters are voltage source, even though the PV is a current source. Current-source inverters are generally used for large motor drives although there have been some PV inverters built using a current source topology. The voltage-source inverter is more popular, with the PWM voltage-source inverter (VSI) dominating the sine-wave inverter topologies.

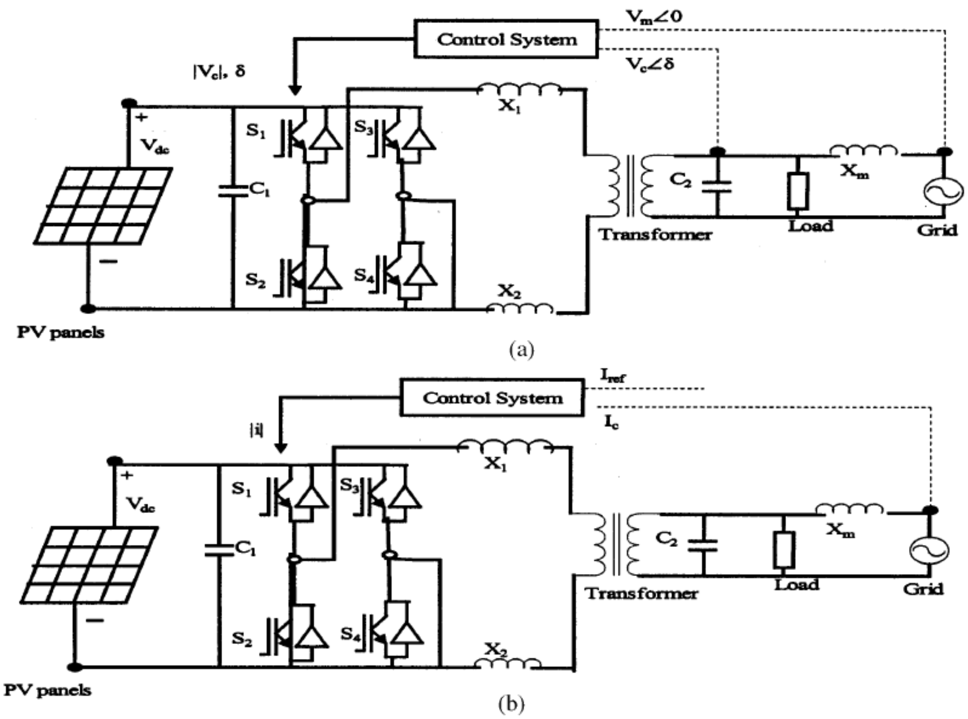


Figure 19: Grid interactive (a) VSI (b) CSI

Fig 19a shows a single-phase full bridge bidirectional voltage source inverter (VSI) with (a) voltage control and phase shift (d) control. The active power transfer from the PV panels is accomplished by controlling the phase angle δ between the converter voltage and the grid voltage. The converter voltage follows the grid voltage. Figure 19b shows the same voltage source inverter operated as a current-controlled inverter (CSI). The objective of this scheme is to control active and reactive components of the current fed into the grid using pulse-width modulation techniques.

6.7.3 Inverter Types

Various types of inverters are in use for grid-connected PV applications, including the following:

1. Line-commutated inverter
2. Self-commutated inverter
3. PV inverter with high-frequency transformer

Line-Commutated Inverter: Line-commutated inverters are generally used for electric-motor applications. The power stage is equipped with thyristors. A maximum-power tracking control is required in the control algorithm for solar application. The basic diagram for a single-phase line-commutated inverter is shown in Fig. 20 [2].

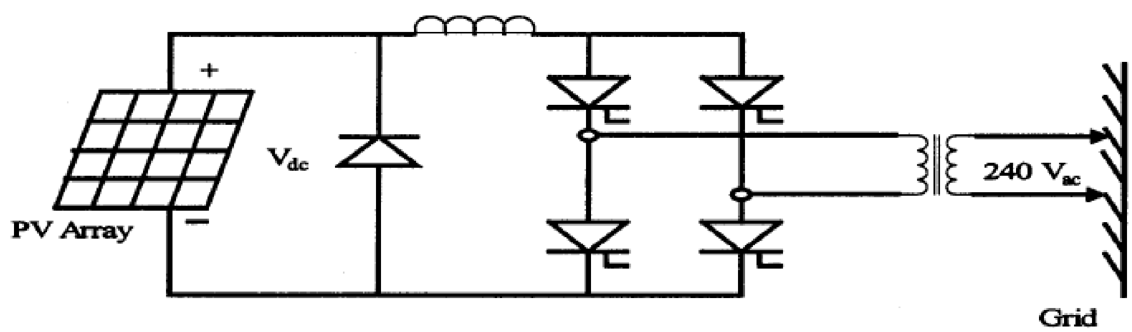


Figure 20: Line commutated single-phase inverter

The driver circuit has to be changed to shift the firing angle from rectifier operation (0^O < f < 90^O) to inverter operation (90^O < f < 180^O). Six-pulse or 12-pulse inverters are used for grid interfacing, but 12-pulse inverters produce fewer harmonics. Thyristors-type inverters require a low-impedance grid interface connection for commutation purposes. If the maximum power available from the grid connection is less than twice the rated PV inverter power, then the line-commutated inverter should not be used [2]. The line-commutated inverters are cheaper but can lead to poor power quality. The harmonics injected into the grid can be large unless taken care of by employing adequate filters. These line-commutated inverters also have poor power factors that require additional control to improve them. Transformers can be used to provide electrical isolation. To suppress the harmonics generated by these inverters, tuned filters are employed and reactive power compensation is required to improve the lagging power factor.

Self-Commutated Inverter: A switch-mode inverter using pulse-width modulated (PWM) switching control can be used for the grid connection of PV systems. The basic block diagram for this type of inverter is shown in Fig. 21. The inverter bridges may consist of bipolar transistors, MOSFET transistors, IGBTs, or GTOs, depending on the type of application. GTOs are used for higher-power applications, whereas IGBTs can be switched at higher frequencies, i.e., 20 kHz, and are generally used for many grid-connected PV applications. Most present-day inverters are self-commutated sine-wave inverters.

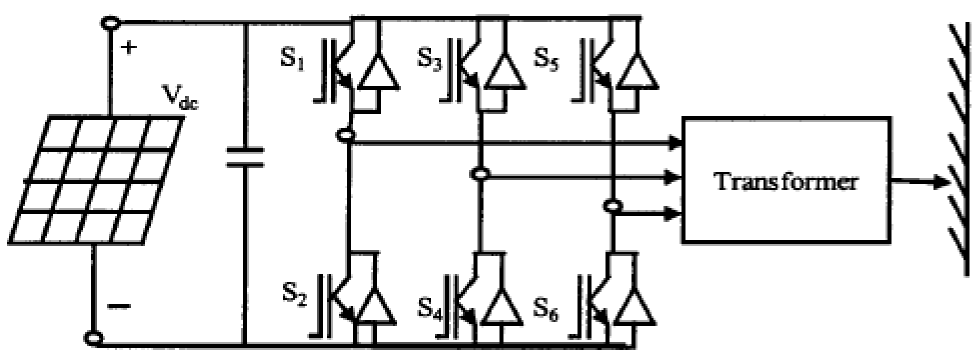


Figure 21: Self commutated inverter with PWM switching

Based on the switching control, voltage-source inverters can be further classified as follows:

- PWM (pulse width modulated) inverters
- Square-wave inverters

- Single-phase inverters with voltage cancellations
- Programmed harmonic elimination switching
- Current-controlled modulation

PV Inverter with High-Frequency Transformer: The 50-Hz transformer for a standard PV inverter with PWM switching scheme can be very heavy and costly. When using frequencies more than 20 kHz, a ferrite core transformer can be a better option [2]. A circuit diagram of a grid connected PV system using high frequency transformer is shown in Fig. 22.

The capacitor on the input side of the high-frequency inverter acts as a filter. The high-frequency inverter with pulse-width modulation is used to produce a high-frequency AC across the primary winding of the high-frequency transformer. The secondary voltage of this transformer is rectified using a high-frequency rectifier. The DC voltage is interfaced with a thyristor inverter through a low-pass inductor filter and hence connected to the grid. The line current is required to be sinusoidal and in phase with the line voltage. To achieve this, the line voltage (V_1) is measured to establish the reference waveform for the line current IL^*. This reference current IL^* multiplied by the transformer ratio gives the reference current at the output of the high-frequency inverter. The inverter output can be controlled using current-controls technique [10]. These inverters can be used with low-frequency or high-frequency transformer isolation. The low-frequency (50/60 Hz) transformer of a standard inverter with pulse-width modulation is a very heavy and bulky component. For residential grid interactive rooftop inverters below 3-kW rating, high-frequency transformer isolation is often preferred.

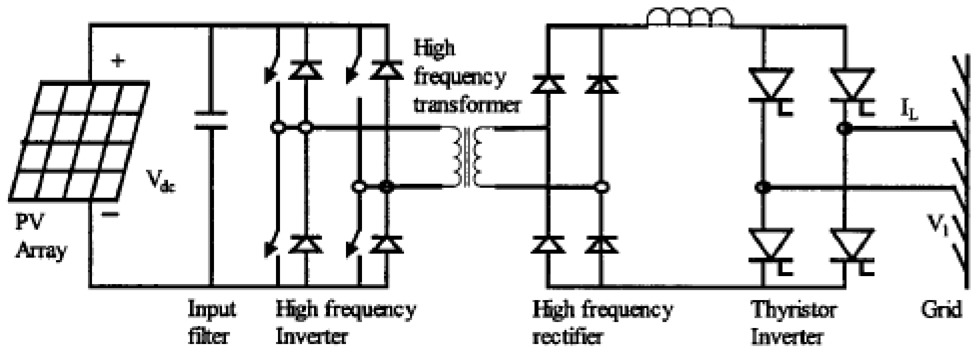


Figure 22: PV inverter with high frequency transformer

6.7.4 Other PV Inverter Topologies

In this section, some of the inverter topologies discussed in various research papers are discussed.

Multilevel Converters Multilevel converters can be used with large PV systems where multiple PV panels can be configured to create voltage steps. These multilevel voltage source converters can synthesize the AC output terminal voltage from different levels of DC voltages and can produce staircase waveforms. This scheme involves less complexity and needs less filtering. One of the schemes (half-bridge diode-clamped three-level inverter [11]) is given in Fig. 23. There is no transformer in this topology. Multilevel converters can be beneficial for large systems in terms of cost and efficiency. Problems associated with shading and malfunction of PV units need to be addressed.

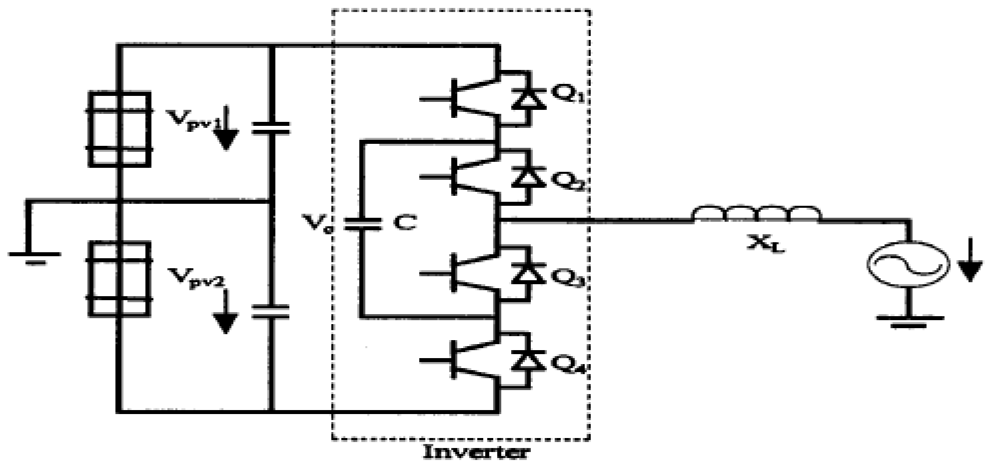


Figure 23: Half bridge diode-clamped three level inverter

Non-insulated Voltage Source In this scheme [12], a string of low-voltage PN panels or one high-voltage unit can be coupled with the grid through a DC-to-DC converter and voltage-source inverter. This topology is shown in Fig. 24. A PWM switching scheme can be used to generate AC output. A filter has been used to reject the switching components.

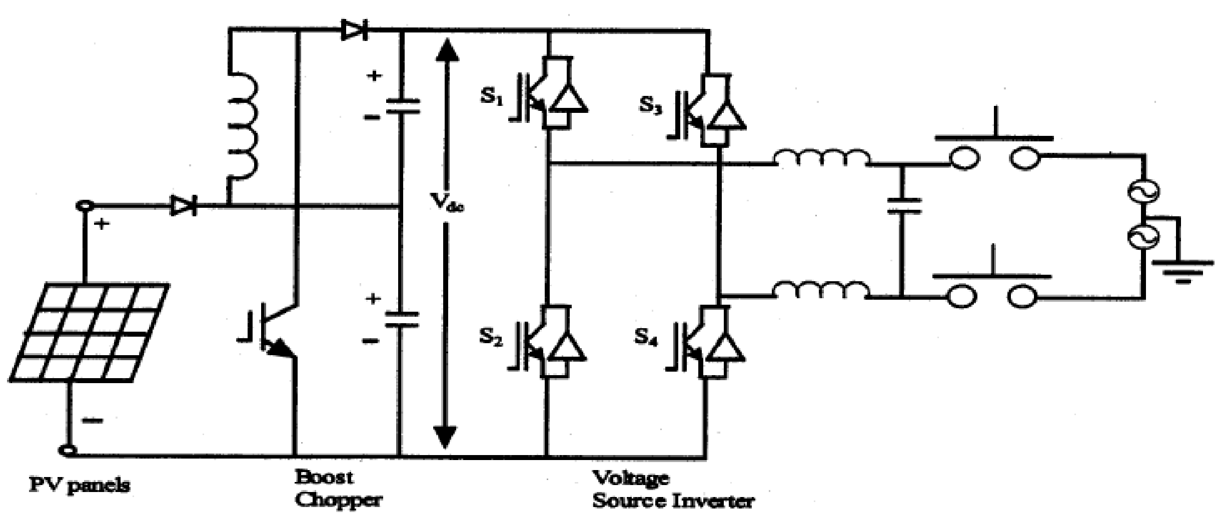


Figure 24: Non-insulated voltage source

Non-insulated Current Source This type of configuration is shown in Fig. 25. Non-insulated current source inverters [12] can be used to interface the PV panels with the grid. This topology involves low cost and can provide better efficiency. Appropriate controllers can be used to reduce current harmonics.

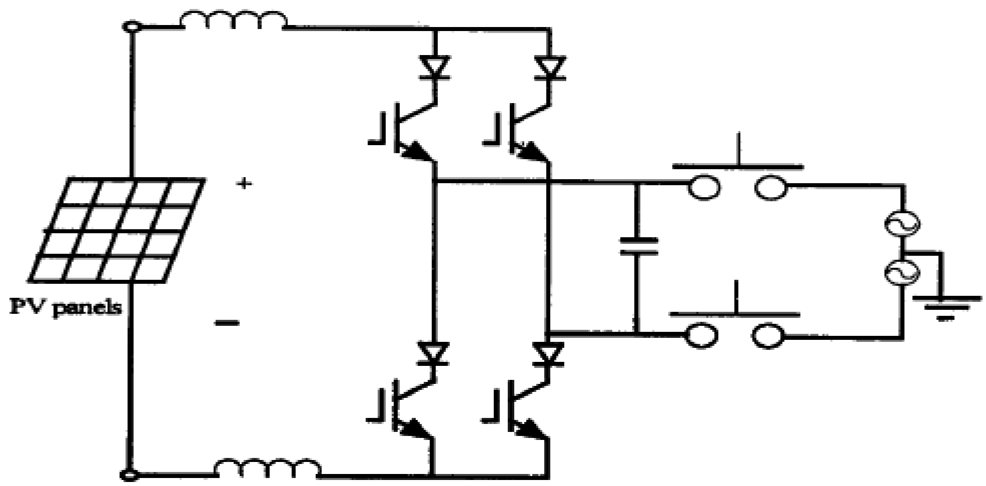


Figure 25: Non-insulated current source

Buck Converter with Half-bridge Transformer Link PV panels are connected to grid via a buck converter and half-bridge as shown in Fig. 26. In this, high-frequency PWM switching has been used at the low-voltage photovoltaic side to generate an attenuated rectified 100-Hz sine wave current waveform [13]. A half-wave bridge is utilized to convert this output to a 50-Hz signal suitable for grid interconnection. To step up the voltage, the transformer has also been connected before the grid connection point.

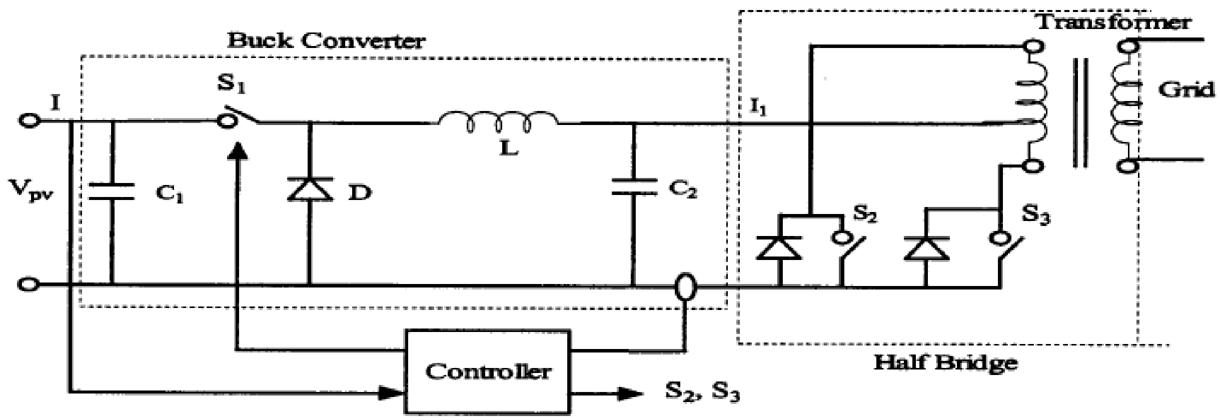


Figure 26: Buck converter with half-bridge transformer link

Flyback Converter This converter topology steps up the PV voltage to DC bus voltage. The PWM-operated converter has been used for grid connection of a PV system in Fig. 27. This scheme is less complex and has fewer switches. Flyback converters can be beneficial for remote areas because of their complex power-conditioning components.

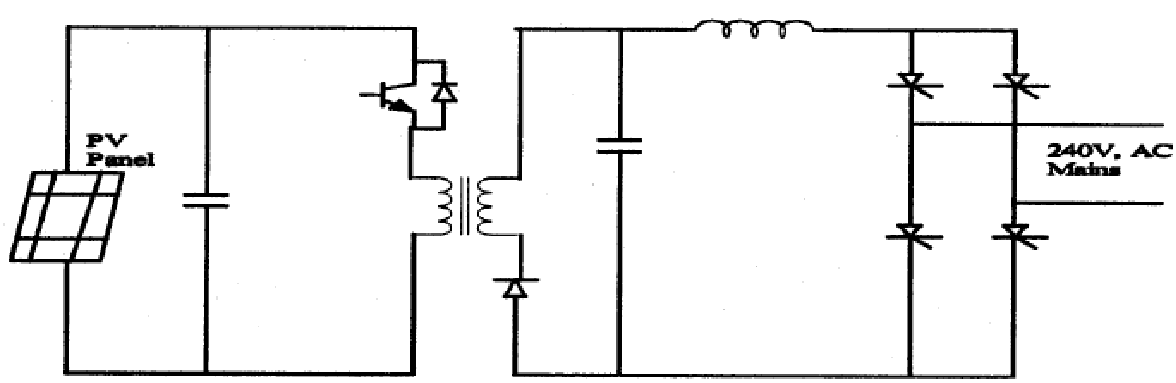


Figure 27: Flyback converter

Interface using Paralleled PV Panels A low-voltage AC bus scheme [14] can be a comparatively efficient and cheaper option. One of the schemes is shown in Fig. 28. A number of smaller PV units can be paralleled together and then connected to a single low-frequency transformer. In this scheme, PV panels are connected in parallel rather than series to avoid problems associated with shading or malfunction of one of panels in series connection.

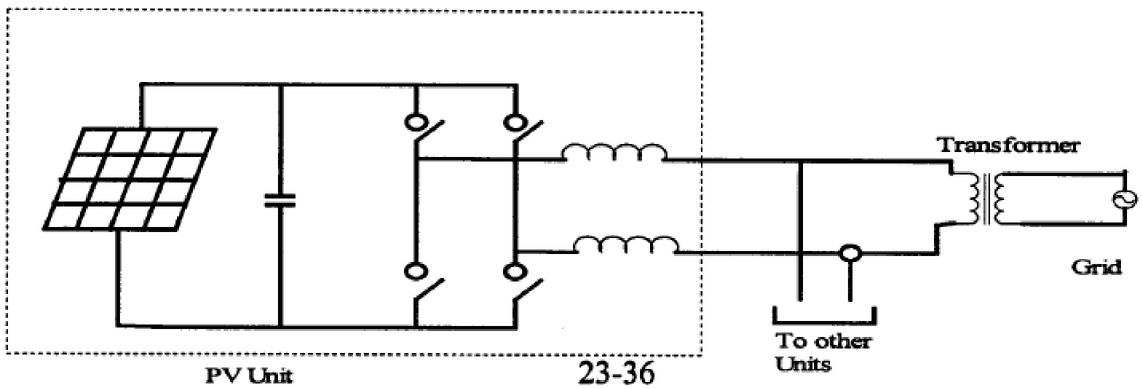


Figure 28: Converter using parallel PV units

6.7.5 Power Control through PV Inverters

The system shown in Fig. 29a shows control of power flow in the grid. This control can be analog or a microprocessor system. This control system generates the waveforms and regulates the waveform amplitude and phase to control the power flow between the inverter and the grid. The grid interfaced PV inverters, voltage-controlled (VCI) or current controlled (CCI), have the potential of bidirectional power flow. They not only can feed the local load, but also can export the excess active and reactive power to the utility grid. An appropriate controller is required in order to avoid any error in power export due to errors in synchronization, which can overload the inverter. A simple grid–inverter interface with a first-order filter and the phasor diagram [15] are shown in Figs. 29a and 29b.

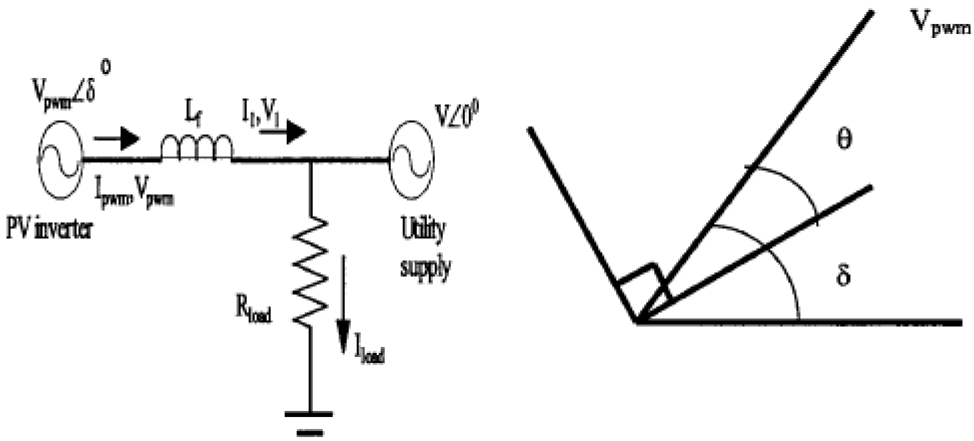


Figure 29: (a) Simple grid interface system (b) Phasor diagram of grid-integrated PV

In the case of voltage controllers, the power equation can be written as [10]:

$$S = P + jQ$$

$$\text{Or } S = \frac{V.V_{pwm}}{X_L}\sin(\delta) + j[\frac{V.V_{pwm}}{X_L}\cos(\delta) - \frac{V^2}{X_L}]$$

whereas for the current controllers [16]:

$$S=V_{pwm}I\cos\theta + j[V_{pwm}I\sin\theta] \tag{6.7}$$

It has been observed that the inverter rated power export is achieved at $\delta=5^{O}$. When using a voltage controller for grid connected PV inverter, it has been observed that a slight error in the phase of synchronizing waveform can grossly overload the inverter whereas a current controller is much less susceptible to voltage phase shifts [15]. For this reason, the current controllers are better suited for the control of power export from the PV inverters to the utility grid since they are less sensitive to errors in synchronizing sinusoidal voltage waveforms.

A prototype current-controlled-type power conditioning system has been developed by the first author and tested on a weak rural feeder line at Kalbarri in Western Australia [17]. The choice may be between additional conventional generating capacities at a centralized location or adding smaller distributed generating capacities using renewable energy sources such as PV. The latter option can have a number of advantages:

1. The additional capacity is added wherever it is required without adding power-distribution infrastructure. This is a critical consideration where the power lines and transformers are already at or close to their maximum ratings.
2. The power conditioning system can be designed to provide much more than just a source of real power, for minimal extra cost. A converter providing real power needs only a slight increase in ratings to handle significant amounts of reactive or even harmonic power. The same converter that converts DC photovoltaic power to AC power can simultaneously provides reactive power support to the weak utility grid.

The block diagram of the power conditioning system used in the Kalbarri project is shown in the Fig. 30. This CC-VSI operates with a relatively narrow switching frequency band near 10 kHz. The control diagram indicates the basic operation of the power conditioning system. The two outer control loops operate to independently control the real and reactive power flow from the PV inverter. The real power is controlled by an outer maximum-power-point tracking (MPPT) algorithm with an inner DC link voltage-control loop providing the real current magnitude request. Ip^* and hence the real power export through PV converter are controlled through the DC link-voltage regulation. The DC link voltage is maintained at a reference value by a PI control loop, which gives the real current reference magnitude as its output. At regular intervals, the DC link voltage is scanned over the entire voltage range to check that the algorithm is operating on the absolute MPP and is not stuck around a local MPP. During the night, the converter can still be used to regulate reactive power of the grid-connected system, although it cannot provide active power. During this time, the PI controller maintains a minimum DC link voltage to allow the power-conditioning system to continue to operate, providing the necessary reactive power. The AC line voltage regulation is provided by a separate reactive power control, which provides the reactive current magnitude reference I_Q^*. The control system has a simple transfer function, which varies the reactive power command in response to AC voltage fluctuations. Common to the outer real and reactive power control loops is an inner higher bandwidth ZACE current control loop. Ip^* is in phase with the line voltages, and I_Q^* is at 90^O to the line voltages. These are added together to give one (per phase) sinusoidal converter current reference waveform (I_{ac}^*). The CC-VSI control consists of analog and digital circuitry that acts as a ZACE transconductance amplifier in converting I_{ac}^* into AC power currents [18].

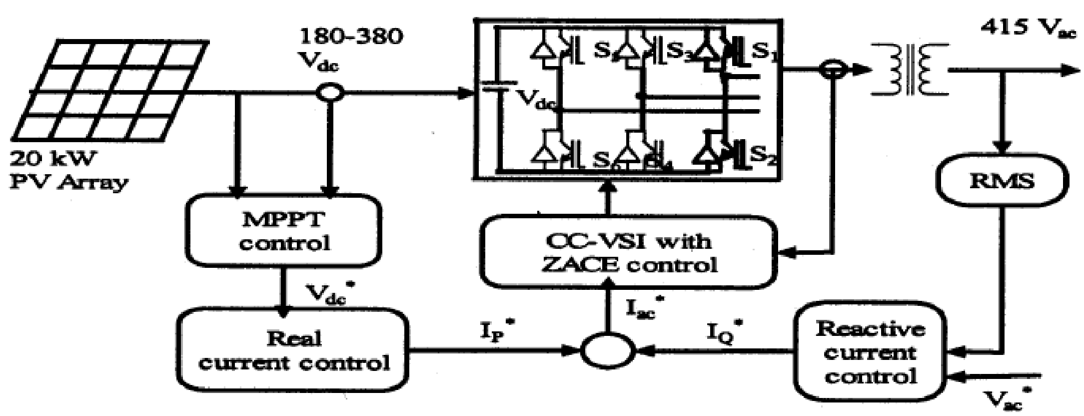


Figure 30: Block diagram of Kalbarri Power Conditioning System

System Configurations

The utility-compatible inverters are used for power conditioning and synchronization of PV output with the utility power. In general, four types of battery-less grid connected PV system configurations have been identified:

1. Central-plant inverter
2. Multiple-string DC–DC converter with single-output inverter
3. Multiple-string inverter
4. Module-integrated inverter

Central-Plant Inverter In the central-plant inverter, usually a large inverter is used to convert DC power output of PV arrays to ac power. In this system, the PV modules are serially strung to form a panel (or string), and several such panels are connected in parallel to a single DC bus. The block diagram of such a scheme is shown in Fig. 31.

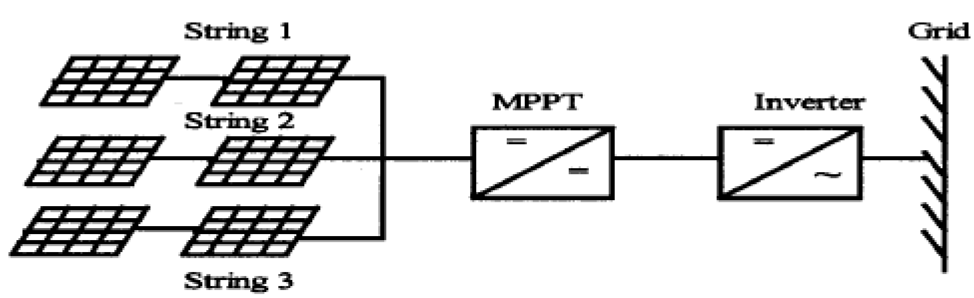


Figure 31: Central plant inverter

Multiple-String DC/DC Converter In the multiple string DC–DC converter, as shown in Fig. 32, each string will have a boost DC–DC converter with transformer isolation. There will be a common DC link, which feeds a transformer-less inverter.

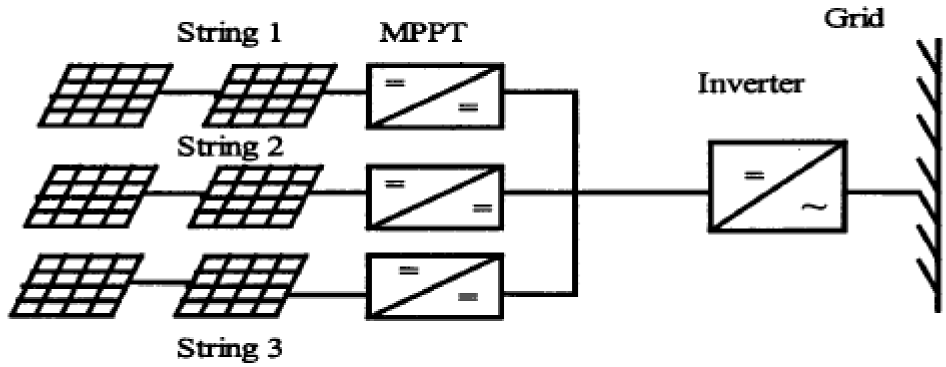


Figure 32: Multiple string DC/DC converter

Multiple-String Inverter Figure 33 shows the block diagram of a multiple-string inverter system. In this scheme, several modules are connected in series on the DC side to form a string. The output from each string is converted to AC through a smaller individual inverter. Many such inverters are connected in parallel on the AC side. This arrangement is not badly affected by shading of the panels. It is also not seriously affected by inverter failure.

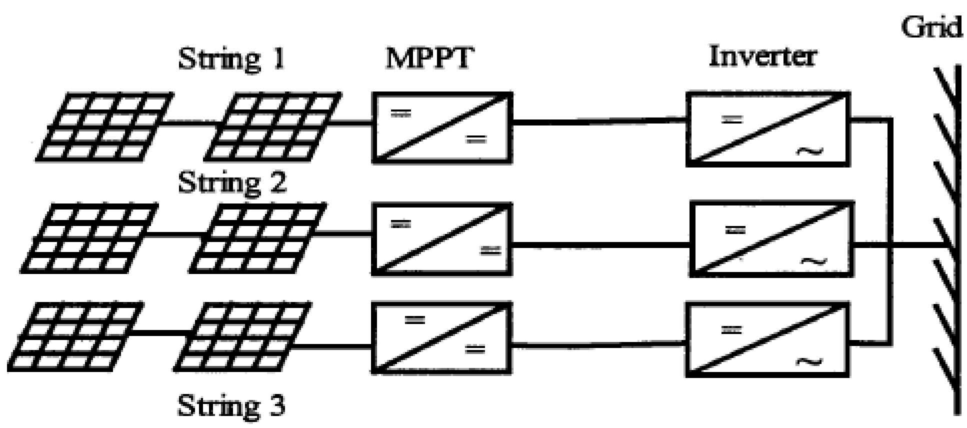


Figure 33: Multiple string inverter

Module-Integrated Inverter In the module-integrated inverter system (Fig. 34), each module (typically 50W to 300W) will have a small inverter. No cabling is required. It is expected that a high volume of small inverters will bring down the cost.

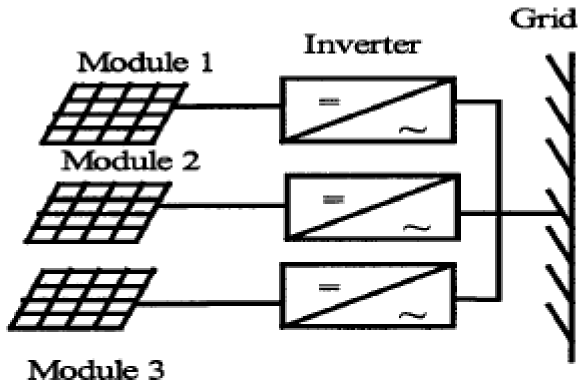


Figure 34: Module integrated inverter

6.7.6 Grid-Compatible Inverter Characteristics

The characteristics of the grid-compatible inverters are:

1. Response time
2. Power factor
3. Frequency control
4. Harmonic output
5. Synchronization
6. Fault current contribution
7. DC current injection
8. Protection

The response time of the inverters must be extremely fast and governed by the bandwidth of the control system. The absence of rotating mass and the use of semiconductor switches allow inverters to respond in a millisecond time frame. The power factor of the inverters is traditionally poor because of the displacement power factor and harmonics. But with the latest developments in inverter technology, it is possible to maintain a power factor close to unity. The converters/inverters have the capability of creating large voltage fluctuations by drawing reactive power from the utility rather than supplying it [19]. With proper control, inverters can provide voltage support by importing/exporting reactive power to push/pull toward a desired set point. This function would be of more use to the utilities as it can assist in the regulation of the grid system at the domestic consumer level.

The frequency of the inverter output wave-shape is locked to the grid. Frequency bias is where the inverter frequency is deliberately made to run at, say, 53 Hz. When the grid is present, this will be pulled down to the nominal 50 Hz. If the grid fails, it will drift upward toward 53Hz and trip on over-frequency. This can help in preventing islanding.

Harmonic output from inverters has traditionally been very poor. Old thyristor-based inverters operated with slow switching speeds and could not be pulse-width modulated. This resulted in inverters known as six-pulse or 12-pulse inverters. The harmonics so produced from the inverters can be injected into the grid, resulting in losses, heating of appliances, tripping of protection equipment, and poor power quality, the number of pulses being the number of steps in a sine-wave cycle. With the present advances in power-electronics technology, inverter controls can be made very good. PWM inverters produce high-quality sine waves. The harmonic levels are very low and can be lower than those of common domestic appliances. If harmonics are present in the grid voltage waveform, harmonic currents can be induced in the inverter. These harmonic currents, particularly those generated by a voltage-controlled inverter, will in fact help in supporting the grid. These are good harmonic currents. This is the reason that the harmonic current output of inverters must be measured onto a clean grid source so that only the harmonics being produced by the inverters are measured.

Synchronization of inverters with the grid is performed automatically and typically uses zero-crossing detection on the voltage waveform. An inverter has no rotating mass and hence has no inertia. Synchronization does not involve the acceleration of a rotating machine. Consequently, the reference waveforms in the inverter can be jumped to any point required within a sampling period. If phase-locked loops are used, the jump could take up a few seconds. Phase-locked loops are used to increase the immunity to noise. This allows the synchronization to be based on several cycles of zero-crossing information. The response time for this type of locking will be slower.

PV panels produce a current that is proportional to the amount of light falling on them. The panels are normally rated to produce 1000W/m^2 at 25^{O}C. Under these conditions, the short circuit current possible from these panels is typically only 20% higher than the nominal current, whereas it is extremely variable for wind. If the solar radiation is low then the maximum current possible under short circuit is going to be less than the nominal full-load current. Consequently, PV systems cannot provide short-circuit capacity to the grid. If a battery is present, the fault current contribution is limited by the inverter. With battery storage, it is possible for the battery to provide the energy. However, inverters are typically limited to between 100% and 200% of nominal rating under current-limit conditions. The inverter needs to protect itself against short circuits because the power electronic components will typically be destroyed before a protection device such as a circuit breaker trip. In case of inverter malfunction, inverters have the capability to inject the DC components into the grid. Most utilities have guidelines for this purpose. A transformer must be installed at the point of connection on the AC side to prevent DC from entering the utility network. The transformer can be omitted when a DC detection device is installed at the point of connection on the AC side in the inverter. The DC injection is essentially caused by the reference or power electronics device producing a positive half-cycle that is different from the negative half-cycle resulting into the DC component in the output. If the DC component can be measured, it can then be added into the feedback path to eliminate the DC quantity.

6.8 Protection Requirements

A minimum requirement to facilitate the prevention of islanding is that the inverter energy system protection operates and isolates the inverter energy system from the grid if any of the following occurs:

1. Overvoltage
2. Under-voltage
3. Over-frequency
4. Under-frequency

These limits may be either factory-set or site-programmable. The protection voltage operating points may be set in a narrower band if required, e.g., 220 V to 260 V. In addition to the passive protection detailed above, and to prevent the situation where islanding may occur because multiple inverters provide a frequency reference for one another, inverters must have an accepted active method of islanding prevention following grid failure, e.g., frequency drift or impedance measurement. Inverter controls for islanding can be designed on the basis of detection of grid voltage, measurement of impedance, frequency variation, or increase in harmonics. This function must operate to force the inverter output outside the protection tolerances specified previously, thereby resulting in isolation of the inverter energy system from the grid. The maximum combined operation time of both passive and active protections should be 2 seconds after grid failure under all local load conditions. If frequency shift is used, it is recommended that the direction of shift be down. The inverter energy system must remain disconnected from the grid until the reconnection conditions are met. Some inverters produce high-voltage spikes, especially at light load, which can be dangerous for the electronic equipment. IEEE P929 gives some idea of the permitted voltage limits.

If the inverter energy system does not have the preceding frequency features, the inverter must incorporate an alternate anti-islanding protection feature that is acceptable to the relevant electricity distributor. If the protection function above is to be incorporated in the inverter, it must be type tested for compliance with these requirements and accepted by the relevant electricity distributor. Otherwise, other forms of external protection relaying are required that have been type tested for compliance with these requirements and approved by the relevant electricity distributor. The inverter must have adequate protection against short-circuit, other faults, and overheating of inverter components.

Chapter 7

Solar photovoltaics

Introduction:

The photovoltaic (pv) power technology uses semiconductor cells (wafers), generally several square centimeters in size. From the solid-state physics point of view, the cell is basically a large area p-n diode with the junction positioned close to the top surface. The cell converts the sunlight into direct current electricity. Numerous cells are assembled in a module to generate required power. Unlike the dynamic wind turbine, the pv installation is static, does not need strong tall towers, produces no vibration or noise, and needs no cooling. Because much of the current pv technology uses crystalline semiconductor material similar to integrated circuit chips, the production costs have been high. However, between 1980 and 1996, the capital cost of pv modules per watt of power capacity has declined.

Solar photovoltaics (SPV):

Solar photovoltaic (SPV) is the process of converting solar radiation into electricity using a device called solar cell. A solar cell is a semi-conducting device made of silicon or other materials, which, when exposed to sunlight, generates electricity.

Factors affecting magnitude of electric current:

1. Intensity of the solar radiation
2. Exposed area of the solar cell
3. Type of material used in fabricating the solar cell
4. Ambient temperature

Hierarchical arrangement:

A hierarchical arrangement of components of PV system is shown in Figure 1.

Advantages of the photovoltaic power:

Major advantages of the photovoltaic power are as follows:

1. Short lead time to design, install, and start up a new plant.
2. Highly modular, hence, the plant economy is not a strong function of size.
3. Power output matches very well with peak load demands.
4. Static structure, no moving parts, hence, no noise.
5. High power capability per unit of weight.
6. Longer life with little maintenance because of no moving parts.
7. Highly mobile and portable because of light weight.

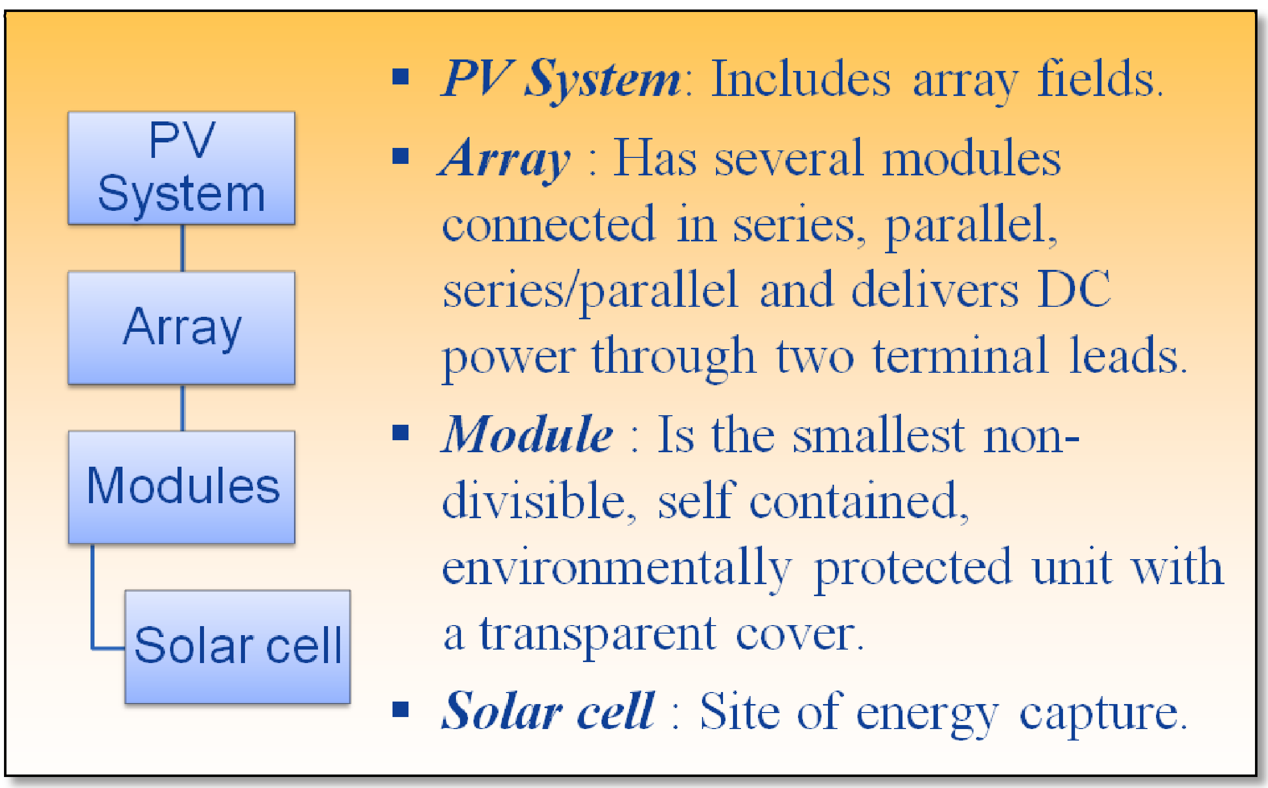


Figure 1: Hierarchical arrangement of elements of PV System

Solar photovoltaic in India:

India is implementing perhaps the most number of pv systems in the world for remote villages. About 30 MW capacity has already been installed, with more being added every year. The country has a total production capacity of 8.5 MW modules per year. The remaining need is met by imports. A 700 kW grid-connected PV plant has been commissioned, and a 425 kW capacity is under installation in Madhya Pradesh. The state of West Bengal has decided to convert the Sagar Island into a PV island. The island has 150,000 inhabitants in 16 villages spread out in an area of about 300 square kilometers. The main source of electricity at present is diesel, which is expensive and is causing severe environmental problems on the island.

The state of Rajasthan has initialed a policy to purchase PV electricity at an attractive rate of $0.08 per kWh. In response, a consortium of Enron and Amoco has proposed installing a 50 MW plant using thin film cells. When completed, this will be the largest PV power plant in the world. The studies at the Arid Zone Research Institute, Jodhpur, indicate significant solar energy reaching the earth surface in India. About 30 percent of the electrical energy used in India is for agricultural needs. Since the availability of solar power for agricultural need is not time critical (within a few days), India is expected to ***lead*** the world in PV installations in near future.

Interesting fact:

One of the attractive features of the pv system is that its power output matches very well with the peak load demand. It produces more power on a sunny summer day when the air-conditioning load strains the grid lines. Power usage curve in commercial building on a typical summer day is shown in Figure 2.

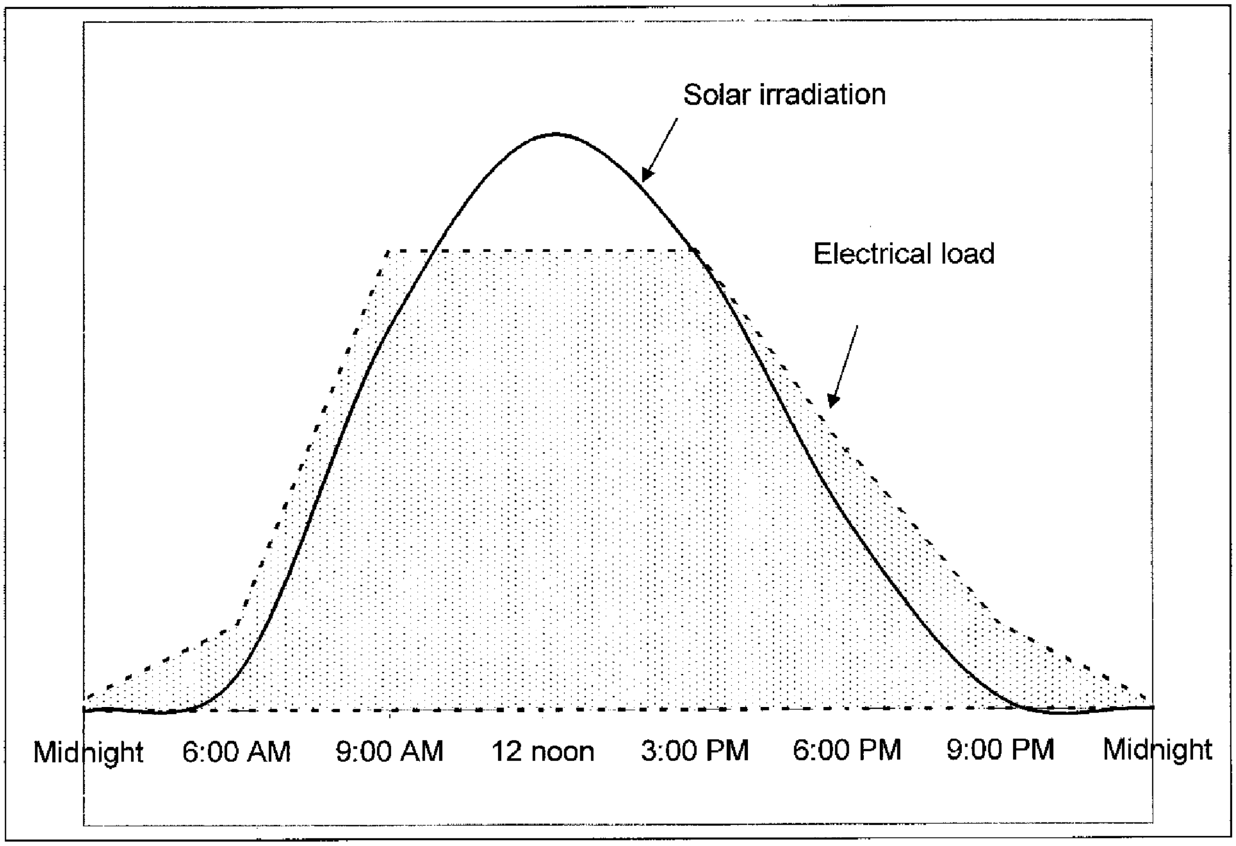


Figure 2: Power usage curve

PV cell technology:

In making comparisons between alternative power technologies, the most important measure is the energy cost per kWh delivered. In pv power, this cost primarily depends on two parameters, the photovoltaic energy conversion efficiency, and the capital cost per watt capacity. Together, these two parameters indicate the economic competitiveness of the pv electricity. The conversion efficiency of the photovoltaic cell is defined as follows:

$$\eta = \frac{Electrical\ power\ output}{Solar\ power\ impinging\ the\ cell}$$

Solar cell:

PV cell is a light sensitive two-terminal N-P junction made of semiconducting material such as silicon. P-type and N-type semiconductor and a solar cell are shown in Figure 3 and 4 respectively.

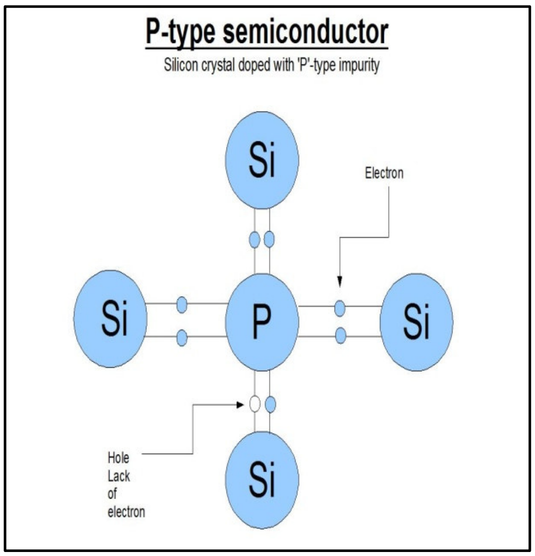


Figure 3: P-Type semiconductor

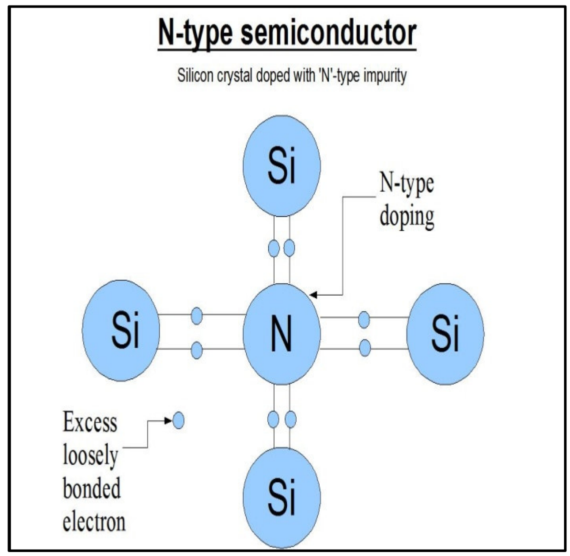


Figure 4: N-Type semiconductor

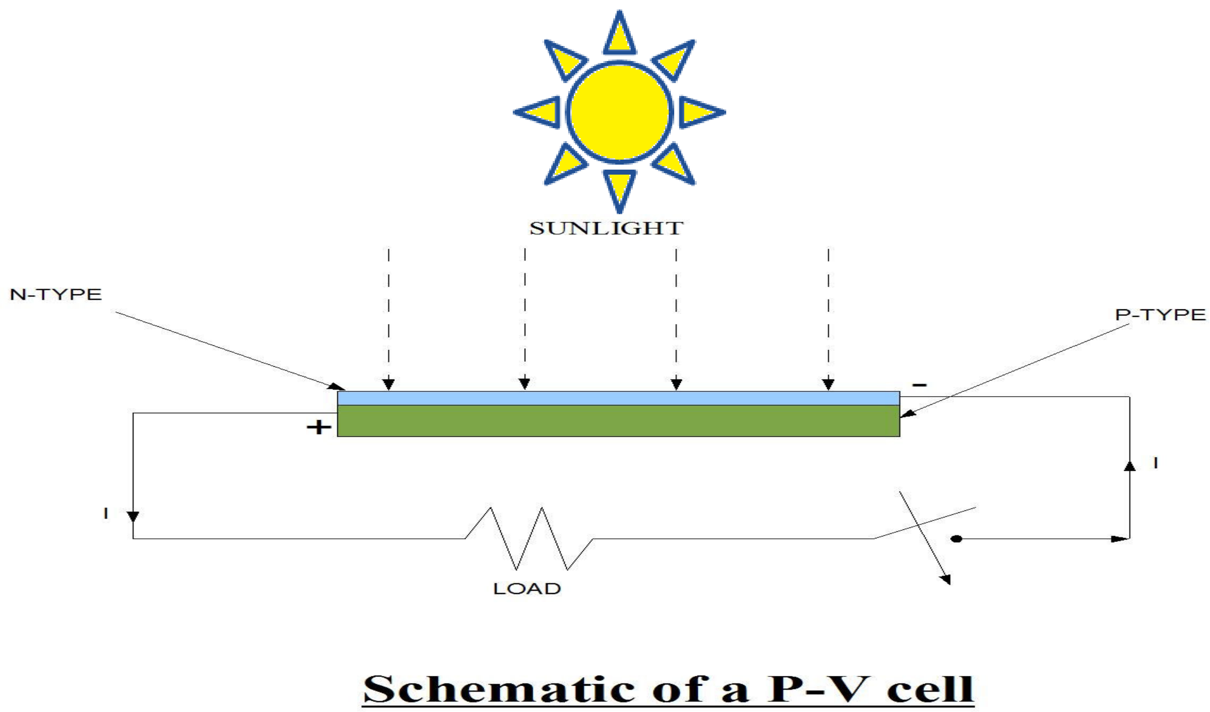


Figure 5: Schematic of a PV cell

Structural analysis of solar cell:

The N-layer is thin and transparent whereas P-layer is thick. When sun-light strikes the N-type thin layer, some of the waves of light energy penetrate up to P-type layer. The energy from photons in the light waves is imparted to the molecules and atoms in the N-P junction resulting in liberation of electron-hole pairs. Electrons are released from N-type material and holes are created in P-type material. This results in flow of current from negative to positive terminal.

Solar cell construction:

Constructing a solar cell involves following important steps:

1. *General design criteria*

2. *Crystal growth:* High purity electronic grade material is obtained in polycrystalline ingots. Impurities should be less than 1 atom in 10^9, i.e. less than 10^{18} atoms per m^3. This starter material has to be made into large single crystals using one of the techniques mentioned below :

    1. *Czochralski technique*
    2. *Zone refining*
    3. *Ribbon growth*
    4. *Vacuum deposition*
    5. *Casting*

3. *Slice treatment*
4. *Modules and arrays*

1. General design criteria of solar cells:

1. Initial materials have to be of high chemical purity with consistent properties.
2. Solar cells are mass produced to minimize cost but high level of precision is vital.
3. Final product has to face hostile weather (-30^0C to $+200^0C$) for as long as 20 years. So, electrical contacts should be firm and corrosion must be avoided. Water must not at all be able to enter the fabric.
4. A few faults must not result in an avalanche leading to full system shutdown.

2. Crystal growth:

Czochralski technique: Czochralski technique of developing crystals of solar cell is explained below:

1. Dip a small seed crystal into molten material.
2. Add dopant (boron acceptors for p type) to melt and pull crystal mechanically upward with a 15 cm dia. crystal growing from the seed.
3. Slice crystal 300 µm thick with highly accurate diamond saws.

Zone refining technique: Zone refining technique of developing crystals of solar cell is explained below:

1. Polycrystalline material is formed as a rod.
2. Molten zone is passed along the rod by heating with a radio frequency coil or lasers.
3. Purified material forms single crystal which is then sliced and treated.

3. Slice treatment:

1. The 300-400 µm thick slices are chemically etched.
2. A very thin layer of N type material is formed by diffusion of donors (e.g. phosphorus) for the top surface by heating the slices to 1000^0C in atmosphere of N_2 in presence of $POCL_3$.
3. *Photolithographic methods*: (Si-Ti-Pd-Ag)
    1. On Si surface, Ti is deposited to form a low resistance contact.
    2. Then thin Pd layer is placed to prevent chemical reaction of Ti with Ag.

3. Finally Ag is deposited for current carrying grid.

4. Modules and arrays:

Individual cells of size 10 x 10 cm are connected into modules of 30 cells. Module consists of 3 to 5 columns of cells in series producing an EMF of 15V which is safe and convenient for charging 12V batteries. Now, a SPV becomes ready for installation at site.

Power of a Solar Panel, Array and Module:

Let n = Number of solar cells in a module;

m= Number of modules in an array or a panel;

P_c=Power per solar cell, watts

Therefore, power per module = n x P_c

Power per array or panel = m x n x P_c

$$P_p = m \times n \times P_c \ \ldots.. \ W$$

For full light, solar panel will deliver power P_p.

Standards for SPV:

1) Bureau of Indian Standards (BIS) establishes the photovoltaic standards in India.

2) Standards specified by BIS for SPV in India relate to areas listed below:

    1. SPV terminology

    2. Measurements of cells and modules

3. Methods of correcting the measurements

4. Qualification test procedure for crystalline silicon modules

5. General description of SPV power generating systems

6. Parameters of stand-alone SPV systems

Standard capacity/ratings and specifications:

1) The wattage output of a PV module is rated in terms of peak watt (W_p) units.

2) The peak watt output that the module could deliver under standard test conditions (STC).

3) STC conditions:

   i) 1000 watts per square meter solar radiation intensity

   ii) Air-mass 1.5 reference spectral distribution

   iii) 25^0C ambient temperature.

4) SPV systems in India are of range $5W_p$-$120W_p$.

Testing and certification of SPV:

The ministry of Non-Conventional Energy Sources (MNES) has established facilities for testing of testing of solar cells, PV modules, and systems at its Solar Energy Center (SEC) in Gurgaon, Haryana.

Other test centers are Electronic Testing and Development Laboratory (ETDC), Bangalore, Electronic Regional Testing Laboratory (ERTL-East), Kolkata and Central Power Research Institute (CPRI), Thiruvananthapuram.

India has currently about 14 companies that manufacture PV modules, and over 45 companies that manufacture SPV systems.

Limits to cell efficiency:

Various factors limit the efficiency of a solar cell. They are mentioned below:

(N.B.: Detailed description of factors mentioned below is provided in Appendix.)

1. Top surface contact obstruction (loss ~3%)
2. Reflection at top surface (loss ~1%)
3. Photon energy less than band gap (loss ~23%)
4. Excess photon energy (loss ~33%)
5. Quantum efficiency (loss ~0.4%)
6. Collection efficiency
7. Voltage factor F_V (loss ~20%)
8. Curve factor F_C (loss ~4%)
9. Additional curve factor A (loss ~5%)
10. Series resistance (loss ~0.3%)
11. Shunt resistance (negligible, ~0.1%)
12. Delivered power (Si cell 10 to 14%)

Experiments in Photovoltaics

Experiment 1

Aim of the Experiment:

This experiment is done to calibrate a solar photovoltaic array and determine its characteristic curve. Also, determine solar radiation intensity at NIT Rourkela.

Appratus Required:

Sl. No.	Name of the equipment	Specifications	Quantity
1	Solar Module	Consisting of 36 solar cells consisting of 4 rows X 9 columns	1
2	Ammeter	0-5A (MC)	1
3	Voltmeter	0-75 V (MI)	1
4	CRO	Dual Trace	1
5	Rheostat	300 Ohm, 1.2A	1
6	Connecting Wires		As required

Experimental Setup and Procedure:

The solar panel at our Electrical Machines laboratory consists of 36 solar cells of about 10 cm diameters each. When direct sunlight falls on this panel, a direct current flows through the entire circuit. Suitable arrangement was made to detect the waveform of the generated current and study its components. The voltmeter and ammeter readings were noted at two different time intervals 3:20 PM and 4:00 PM IST. Rourkela is located at latitude 25^{O}N and longitude 85^{O}E.

Observations:

Run 1: (Time of observation: 2:30 PM IST)

Voltage (V)	18.2	17.7	17.12	16.7	16.5	16.02	15.43	0 (SHORT CIRCUIT)
Current (A)	0 (OPEN CIRCUIT)	0.1	0.2	0.3	0.4	0.5	0.6	0.95

Run 2: (Time of observation: 3:30 PM IST)

Voltage (V)	18.1	17.49	16.82	16.18	15.45	14.43	11.70	0 (SHORT CIRCUIT)
Current (A)	0 (OPEN CIRCUIT)	0.1	0.2	0.3	0.4	0.5	0.6	0.65

Results :

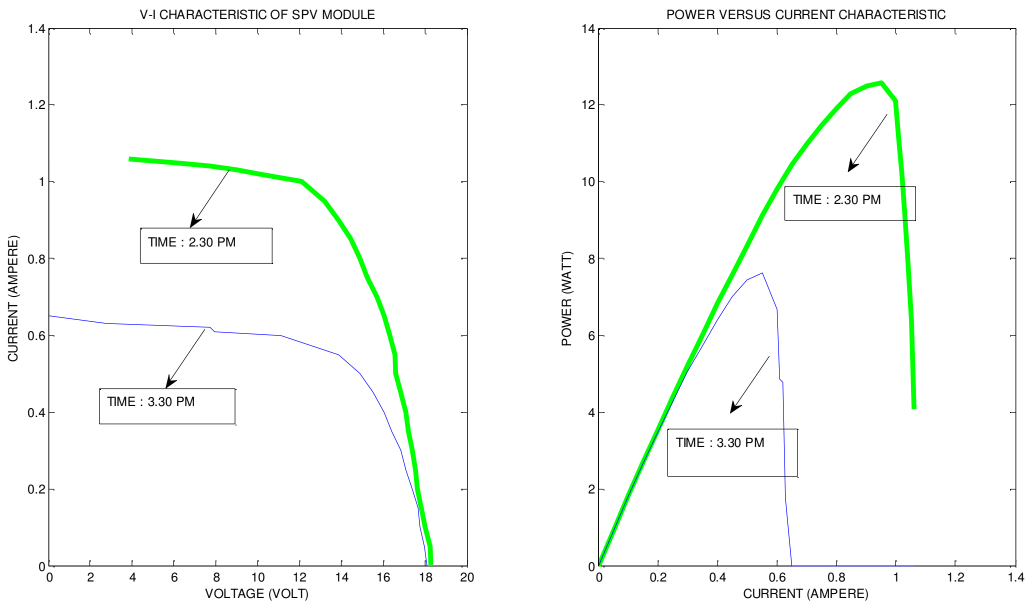


Figure 6: Effect of time on I-V and P-I curve

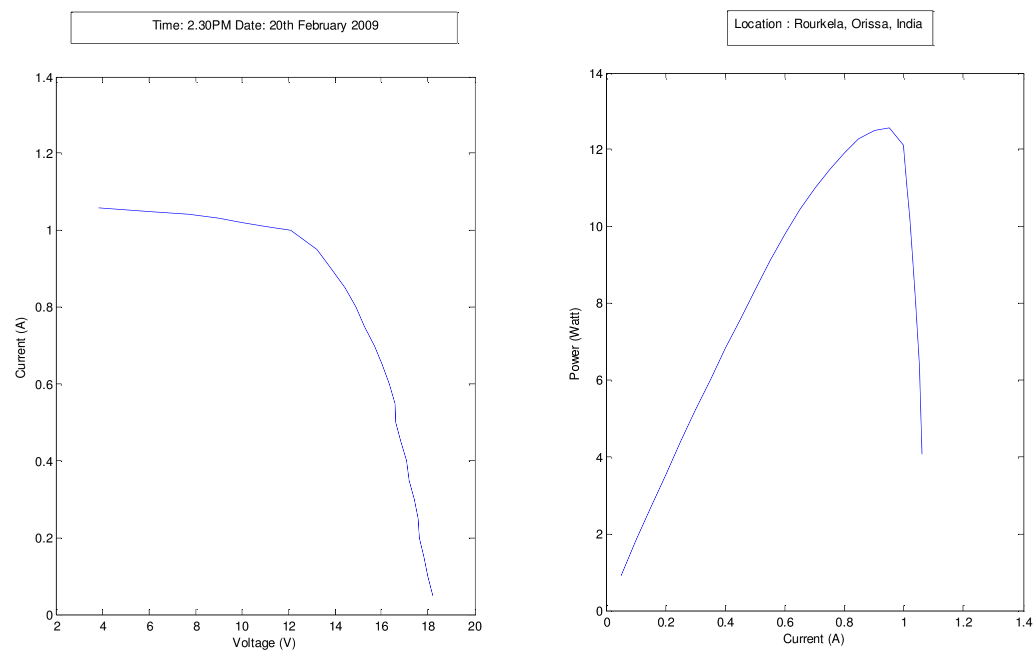


Figure 7: V-I and P-I characteristics of SPV Module

Explanation of Graphs:

Voltage and current readings obtained after experiment are shown graphically in figure 6. Knee point of operation provides maximum output from a solar cell. It is obtained from figure 7.

Conclusion:

The graph obtained is in agreement with the ideal efficiency curve.

Calculations:

$$\text{Efficiency of solar cell} = \frac{\textit{Amount of solar power incident on cells}}{\textit{Amount of electricity power generated}}$$

Let n = Number of solar cells in a module;

m= Number of modules in an array or a panel;

Pc=Power per solar cell, watts

Power per module = n x Pc

Power per array or panel = m x n x Pc

Pp = m x n x Pc ….. W

For full light, solar panel will deliver power Pp.

At NIT Rourkela, amount of electricity produced = 10% of incident energy

Also, diameter of a solar cell = 10 cm

Area of 1 PV cell = $\frac{\pi}{4}D^2$ = 78.57 cm^2

No. of PV cells in array = 4 (columns) X 9 (rows) i.e. m=4, n=9

Total exposed area of cells = 36 X 78.57 = 0.283 m^2

Radiation Intensity = $\frac{\text{Power generated}}{\text{Area}}$ = 864 W/m^2

COST ANALYSIS

Component	Unit Price (Rupees)	Qty	Total Price (Rs.)	Output DC Voltage (V)	Capacity	% Contribution to total cost
Modular Arrays	2,580.49	8	20,643.92	12	N/A	34.54
Batteries	5,000.00	4	20,000.00	12	65 AH	33.46
Charge Controllers	3,000.00	4	12,000.00	12	N/A	20.00
Mounting	1,280.50	4	05,122.00	N/A	N/A	08.60
Cabling	0500.00	4	02,000.00	N/A	N/A	03.40
TOTAL			***59,765.92***	**TOTAL**		***100.0***

Modular Array

Consumption (W)	Efficiency of panel (%)	Insolation (W/m^2)	Area Required	Size of Array	No of array
300	15	864	2.26	0.283	8

Load	Wattage (W)	Assumed Usage (hr)	Consumption (Wh)	Qty	Total Consumption (kWh)
Solar lamps	15	12	180	35	6.3

Batteries	kWh
Capacity	1.5
No . needed / blk	4
No. needed /blk for 3 days	12

Inverters	W	Charge Controllers	W
Capacity	500	Maximum Power	90
No. needed / battery	3	No. required	4

Experiment 2

Aim of the experiment:

Voltage analysis of a load receiving power from a nearby solar photovoltaic power module.

Theory:

The **duty cycle** is the fraction of time during which the switch is on. For control purposes the pulse width can be adjusted to achieve a desired result. This adjustment process is called pulse-width modulation (PWM), perhaps the most important process for implementing control in power converters.

Frequency is mostly constant and is often dictated by the application.

PWM inverters produce high-quality sine waves. The harmonic levels are very low and can be lower than those of common domestic appliances.

PWM techniques: In single PWM, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output voltage.

In sinusoidal modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse.

<u>Appratus Required:</u>

Sl. No.	Name of the equipment	Specifications	Quantity
1	**Solar Module**	**Consisting of 36 solar cells (4 rows X 9 columns)**	**1**
2	**Ammeter**	**0-5A (MC)**	**1**
3	**Voltmeter**	**0-75 V (MI)**	**1**
4	**CRO**	**Storage type**	**1**
5	**Rheostat**	**50 Ohm, 1.2A**	**1**
6	**Inductor**	**50 mH,100 mH,250 mH**	**3**
7	**Interfacing cord**	**For connecting CRO to desktop**	**1**
8	**TekVision Software**	**Installed on desktop**	**-**
6	**Connecting Wires**		**As required**

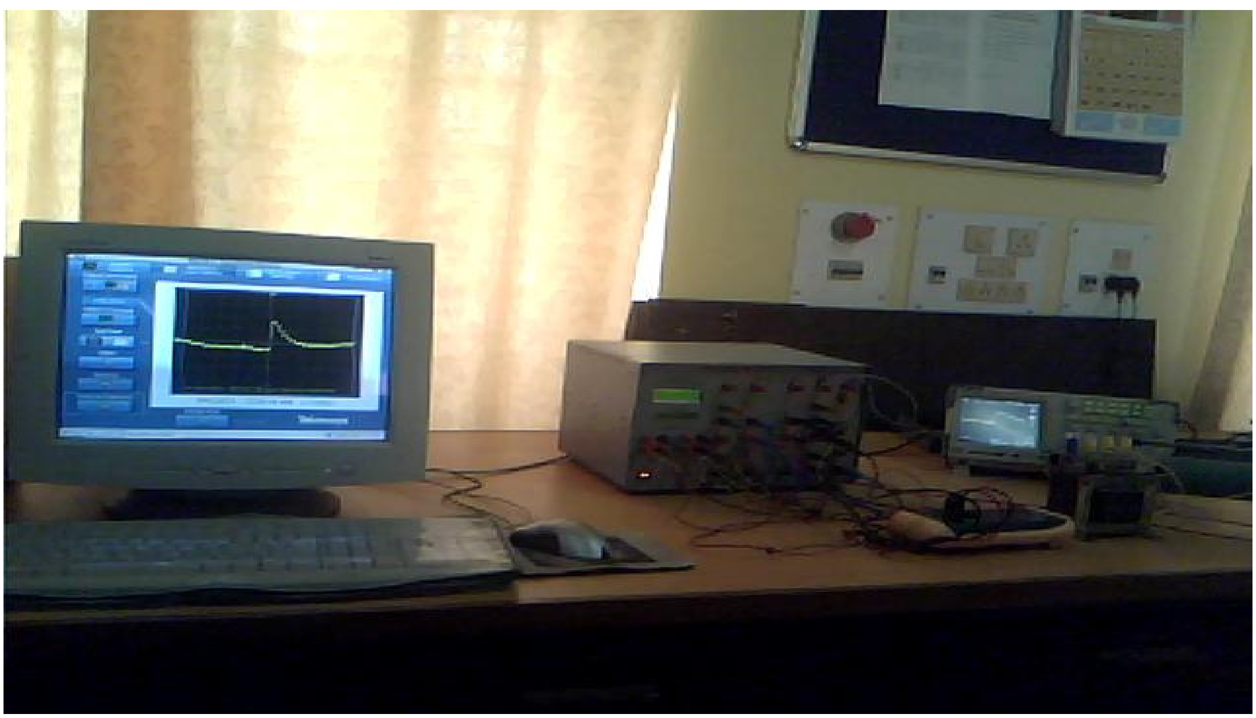
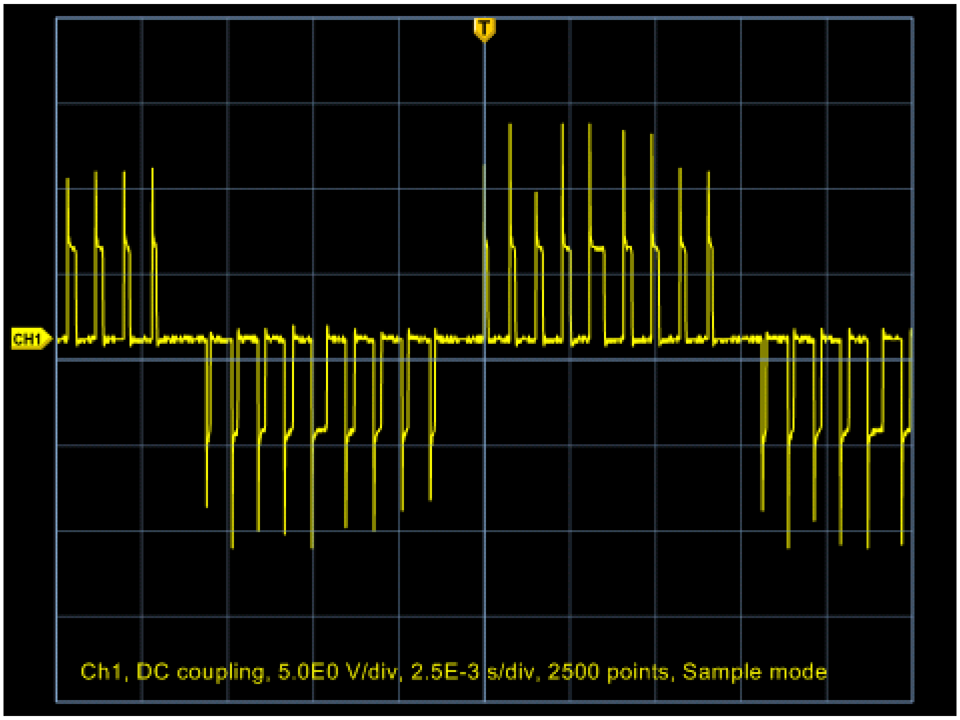


Figure 6: EXPERIMENTAL SETUP

Waveform:



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Discussion:

This experiment is used to study the AC voltage waveform from the output of inverter. But due to harmonics and resonance the waveform obtained was not pure sine wave.

Calculating savings using PV Walls software:

This calculation is based on best and most recent statistics available from server.

AC Energy
&
Cost Savings

Station Identification	
City:	Calcutta
Country/Province:	IND
Latitude:	22.65° N
Longitude:	88.45° E
Elevation:	6 m
Weather Data:	IWEC
PV System Specifications	
DC Rating:	4.00 kW
DC to AC Derate Factor:	0.770
AC Rating:	3.08 kW
Array Type:	Fixed Tilt
Array Tilt:	22.6°
Array Azimuth:	180.0°
Energy Specifications	
Energy Cost:	3.00 rupee/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value (rupee)
1	4.86	418	1254
2	5.43	412	1236
3	6.00	494	1482
4	6.08	475	1425
5	5.57	450	1350
6	4.56	365	1095
7	4.00	332	996
8	4.26	355	1065
9	4.31	347	1041
10	4.89	399	1197
11	4.70	381	1143
12	4.72	403	1209
Year	4.94	4831	14493

Chapter 8

PEM Fuel Cell

POLYMER ELECTROLYTE MEMBRANE FUEL CELLS

Polymer electrolyte membrane fuel cells (PEFC) are able to efficiently generate high power densities, thereby making the technology potentially attractive for certain mobile and portable applications. Especially the possible application of PEFC as a prime mover for automobiles has captured the imagination of many. PEFC technology differentiates itself from other fuel cell technologies in that a solid phase polymer membrane is used as the cell separator/electrolyte. Because the cell separator is a polymer film and the cell operates at relatively low temperatures, issues such as sealing, assembly, and handling are less complex than most other fuel cells. The need to handle corrosive acids or bases is eliminated in this system. PEFCs typically operate at low temperatures (60^{O} to $80^{O}C$), allowing for potentially faster startup than higher temperature fuel cells. The PEFC is seen as the main fuel cell candidate technology for light-duty transportation applications. While PEFC are particularly suitable for operation on pure hydrogen, fuel processors have been developed that will allow the use of conventional fuels such as natural gas or gasoline. A unique implementation of the PEFC allows the direct use of methanol without a fuel processor; it is the direct methanol fuel cell (DMFC). The DMFC is seen as the leading candidate technology for the application of fuel cells to cameras, notebook computers, and other portable electronic applications.

8.1 Cell Components

Typical cell components within a PEFC stack include:

- the ion exchange membrane
- an electrically conductive porous backing layer
- an electro-catalyst (the electrodes) at the interface between the backing layer and the membrane
- cell interconnects and flow-plates that deliver the fuel and oxidant to reactive sites via flow channels and electrically connect the cells (Figure 1 & 2).

PEFC stacks are almost universally of the planar bipolar type. Typically, the electrodes are cast as thin films that are either transferred to the membrane or applied directly to the membrane. Alternatively, the catalyst-electrode layer may be deposited onto the backing layer, then bonded to the membrane.

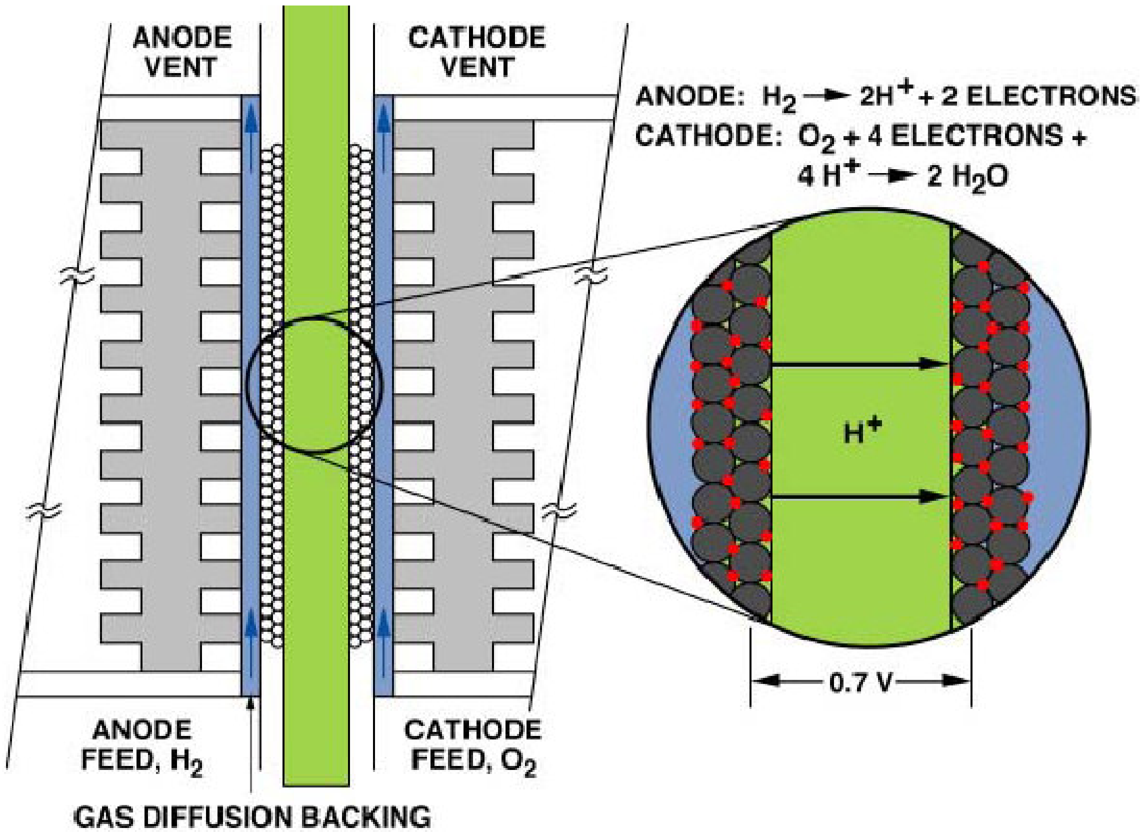

Figure 1: Schematic of PEFC

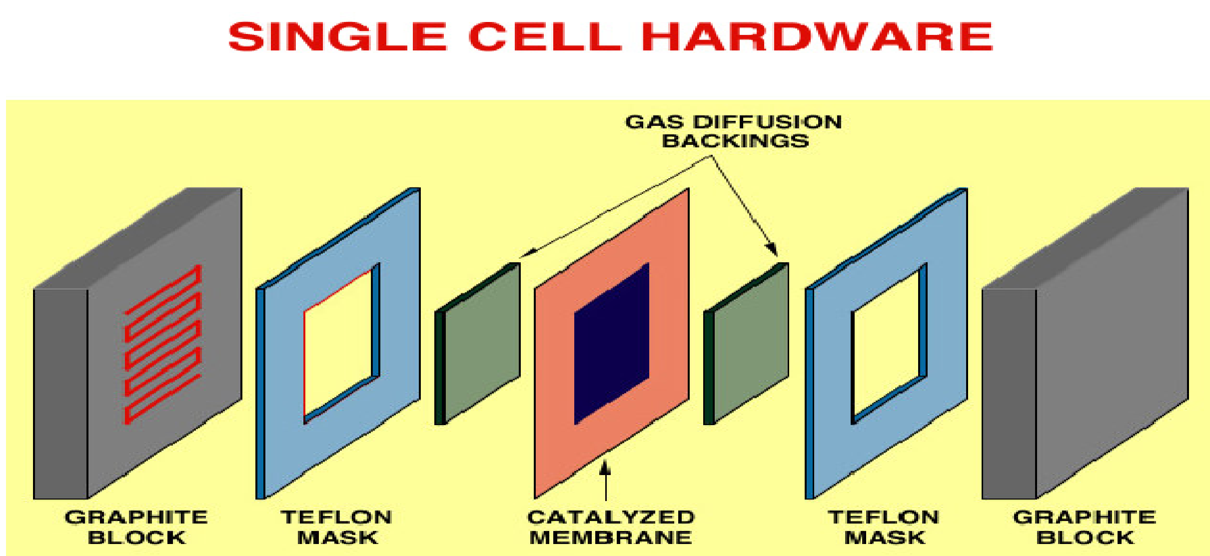

Figure 2: Single Cell Structure of PEFC

8.1.1 Membrane

Organic-based cation exchange membranes in fuel cells were originally conceived by William T. Grubb (2) in 1959. That initial effort eventually led to development of the perfluorosulfonic acid polymer used in today’s systems. The function of the ion exchange membrane is to provide a conductive path, while at the same time separating the reactant gases. The material is an electrical insulator. As a result, ion conduction takes place via ionic groups within the polymer structure. Ion transport at such sites is highly dependent on the bound and free water associated with those sites. An accelerated interest in polymer electrolyte fuel cells has led to improvements in both cost and performance. Development has reached the point where both motive and stationary power applications are nearing an acceptable cost for commercial markets. Operation of PEFC membrane electrode assemblies (MEAs) and single cells under laboratory conditions similar to transportation or stationary applications have operated for over 20,000 hrs continuously with degradation rates of 4 to 6 ⌠V/hr (or about 0.67 to 1.0 percent per 1000 hrs), which approaches the degradation rates needed for stationary applications (about 0.1 percent per 1000 hrs is used as a rule of thumb). Complete fuel cell systems have been demonstrated for a number of transportation applications including public transit buses and passenger automobiles. For stationary applications, a number of demonstration systems have been developed and numerous systems have been installed, mostly in the 2 to 10 kW range. However, although these systems have collectively logged millions of kWhrs (3), developers have not yet demonstrated system or stack life of more than 8,000 hours with realistic catalyst loadings and realistic operating conditions, and then with degradation rates of several percent per 1000 hrs. Consequently, PEFC developers and researchers are focused on achieving critical improvements in extending stack life, simpler system integration, and reduction of system cost. This is true both for stationary and mobile applications.

8.1.2 Porous Backing Layer

The polymer membrane is sandwiched between two sheets of porous backing media (also referred to as gas diffusion layers or current collectors). The functions of the backing layer[8] are to:

(1) act as a gas diffuser;

(2) provide mechanical support,

(3) provide an electrical pathway for electrons, and

(4) channel product water away from the electrodes.

The backing layer is typically carbon-based, and may be in cloth form, a non-woven pressed carbon fiber configuration, or simply a felt-like material. The layer incorporates a hydrophobic material, such as polytetrafluoroethylene. The function of polytetrafluoroethylene is to prevent water from “pooling” within the pore volume of the backing layer so that gases freely contact the catalyst sites. Furthermore, it facilitates product water removal on the cathode as it creates a non-wetting surface within the passages of the backing material.

One PEFC developer (10) devised an alternative plate structure that provides passive water control. Product water is removed by two mechanisms:

(1) transport of liquid water through the porous bipolar plate into the coolant, and

(2) evaporation into the reactant gas streams.

The cell is similar in basic design to other PEFCs with membrane, catalysts, substrates, and bipolar plate components. However, there is a difference in construction and composition of the bipolar plate: it is made of porous graphite. During operation, the pores are filled with liquid water that communicates directly with the coolant stream. Product water flows from the cathode through the pores into the coolant stream (a small pressure gradient between reactant and the coolant stream is needed). The water in the coolant stream is then routed to a reservoir. Removal of water by the porous membrane results in the reactant flow stream being free of any obstructions (liquid water). The flooded pores serve a second purpose of supplying water to the incoming reactant gases and humidifying those gases. This prevents drying of the membrane, a common failure mode, particularly at the anode. Control of the amount of area used to humidify the inlet gases has eliminated the need to pre-humidify the reactant gases.

Reasons for removing the water through the porous plate are:

(1) there is less water in the spent reactant streams;

(2) this approach reduces parasitic power needs of the oxidant exhaust condenser;

(3) the cell can operate at high utilizations that further reduce water in the reactant streams;

(4) higher temperatures can be used with higher utilizations so that the radiator can be smaller,

(5) the control system is simplified.

In fact, in-stack water conservation is even more important in arid climates, where there may exist a significant challenge to achieve water balance at the system level without supplying water or refrigerating the exhaust stream. Hand-in-hand with water management goes the thermal management of the stack. Temperatures within the stack must be kept within a narrow range in order to avoid local dehydration and hotspots as well as local dead zones. This is particularly challenging when one recognizes the narrow temperature zone and the relatively small temperature difference between the cell operating temperature and the ambient temperature.

8.2 Performance

Because of changes in operating conditions involving pressure, temperature, reactant gases, and other parameters, a wide range of performance levels can be obtained. The performance of the PEFC in the U.S. Gemini Space Program was 37 mA/cm^2 at 0.78 V in a 32- cell stack that typically operated at 50°C and 2 atmospheres. Current technology yields performance levels that are vastly superior. Results from Los Alamos National Laboratory show that 0.78 V at about 200 mA/cm^2 (3 atmospheres H_2 and 5 atmospheres air) can be obtained at 80

°C in PEFCs containing a Nafion membrane and electrodes with a platinum loading of 0.4 mg/cm^2. Further details on PEFC performance with Nafion membranes are presented by Watkins, et al. . In recent years, the development effort has been focused on maintaining power density while reducing platinum loading, broadening temperature and humidity operating envelopes, and other improvements that will reduce cost (14 ,11).

Operating temperature has a significant influence on PEFC performance. An increase in temperature decreases the ohmic resistance of the electrolyte and accelerates the kinetics of the electrode reactions. In addition, mass transport limitations are reduced at higher temperatures. The overall result is an improvement in cell performance. Experimental data suggest a voltage gain in the range of 1.1 - 2.5 mV for each degree (°C) of temperature increase. Operating at higher temperatures also reduces the chemisorption of CO. Improving the cell performance through an increase in temperature, however, is limited by the vapor pressure of water in the ion exchange membrane due to the membrane's susceptibility to dehydration and the subsequent loss of ionic conductivity.

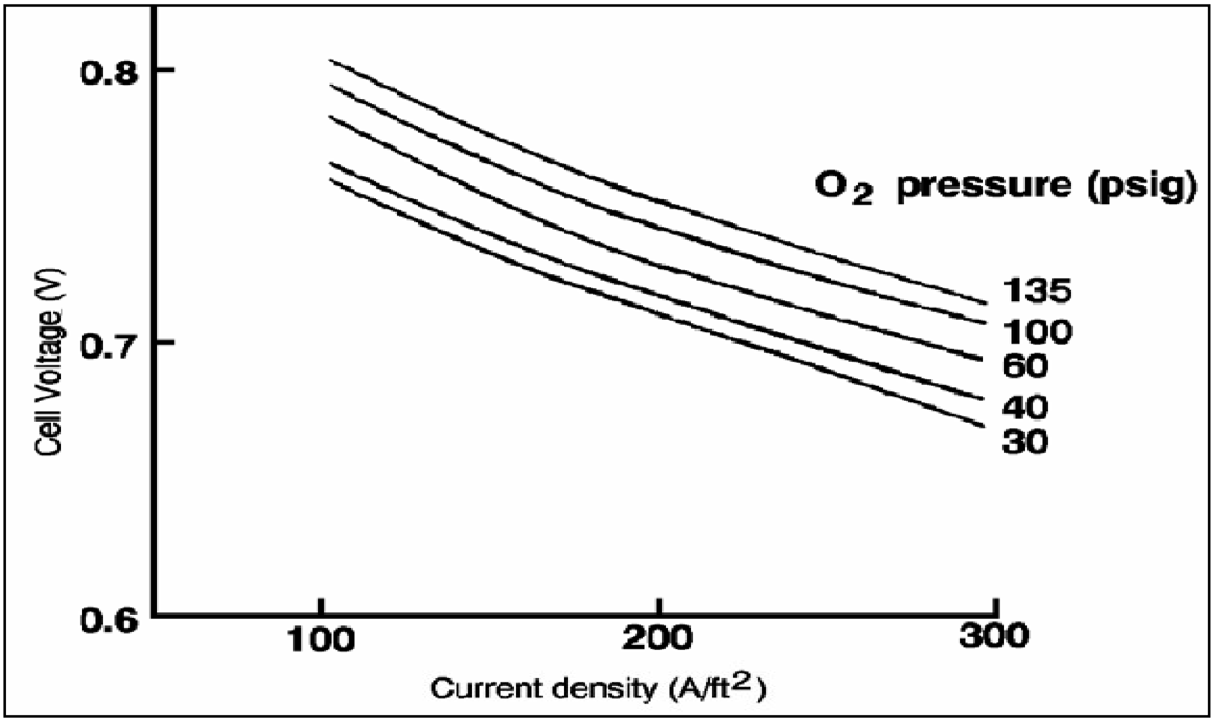

Figure 3: Plot of Cell Voltage Vs Current Density for different Oxygen pressure

Operating pressure also impacts cell performance. The influence of oxygen pressure on the performance of a PEFC at 93°C is illustrated in Figure 3. An increase in oxygen pressure from 30 to 135 psig (3 to 10.2 atmospheres) produces an increase of 42 mV in the cell voltage at 215 mA/cm^2. According to the Nernst equation, the increase in the reversible cathode potential that is expected for this increase in oxygen pressure is about 12 mV, which is considerably less than the measured value. When the temperature of the cell is increased to 104°C, the cell voltage increases by 0.054 V for the same increase in oxygen pressure. Additional data suggest an even greater pressure effect. A PEFC at 50°C and 500 mA/cm^2 exhibited a voltage gain of 83 mV for an increase in pressure from 1 to 5 atmospheres. Another PEFC at 80°C and 431 mA/cm^2 showed a voltage gain of 22 mV for a small pressure increase from 2.4 to 3.4 atmospheres. These results demonstrate that an increase in the pressure of oxygen results in a significant reduction in polarization at the cathode. Performance improvements due to increased pressure must be balanced against the energy required to pressurize the reactant gases. The overall system must be optimized according to output, efficiency, cost, and size.

8.3 PEFC Applications

8.3.1 Transportation Applications

The focus for PEFC applications of PEFC today is on prime power for cars and light trucks. PEFC is the only type of fuel cell considered for prime motive power in on-road vehicles (as opposed to APU power, for which SOFC is also being developed). PEFC systems fueled by hydrogen, methanol, and gasoline have been integrated into light duty vehicles by at least twelve different carmakers. Early prototypes of fuel cell vehicles (Honda and Toyota) have been released to controlled customer groups in Japan and the U.S. However, all automakers agree that the widespread application of PEFC to transportation will not occur until well into the next decade:

- Volume and weight of fuel cell systems must be further reduced
- Life and reliability of PEFC systems must be improved

- PEFC systems must be made more robust in order to be operable under the entire range of environmental conditions expected of vehicles
- Additional technology development is required to achieve the necessary cost reductions
- A hydrogen infrastructure, and the accompanying safety codes and standards must be developed.

8.3.2 Stationary Applications

Several developers are also developing PEFC systems for stationary applications. These efforts are aimed at very small-scale distributed generation (~1 to 10 kW AC). The vast majority of systems are designed for operation on natural gas or propane. Hundreds of demonstration units have been sited in programs in the U.S., Europe, and Japan. Typical performance characteristics are given by Plug Power. Considerable progress has been made in system integration and in achieving stand-alone operation. System efficiency typically ranges from 25 to 32 percent (based on LHV). By recovering the waste heat from the cooling water, the overall thermal efficiency can be raised to about 80 percent, but the water temperature (about 50 to 70 °C) is rather modest for many CHP applications. System operating life has been extended to about 8,000 hrs for a single system with a single stack, with degradation of about 5 percent per 1,000 hours.

8.4 MATLAB Implementation of PEM Fuel Cell:

8.4.1: Program to study variation of ohmic loss with electrolyte thickness

```
% CALCULATING OHMIC VOLTAGE LOSS

% INPUTS

i=0.7; % Current Density (A/cm^2)

A=100; % Area (cm^2)

L=0.0050; % Electrolyte thickness (cm)

sigma=0.1; % Conductivity (ohms/cm)

R_elec=0.005; % Electrical resistance (ohms)

% CALCULATE THE TOTAL CURRENT

I=i*A;

% CALCULATE THE TOTAL IONIC RESISTANCE

R_ohmic=L/(sigma*A);

% CALCULATE THE OHMIC VOLTAGE LOSS

V_ohm=I.*(R_elec+R_ohmic)

i=0:0.01:1; % CURRENT RANGE

L1=0.0025; % ELECTROLYTE THICKNESS OF 25 MICRONS

L2=0.005; % ELECTROLYTE THICKNESS OF 50 MICRONS

L3=0.0075; % ELECTROLYTE THICKNESS OF 75 MICRONS

L4=0.01; % ELECTROLYTE THICKNESS OF 100 MICRONS

L5=0.015; % ELECTROLYTE THICKNESS OF 150 MICRONS

% CALCULATE THE TOTAL CURRENT

I=i*A;

% CALCULATE THE OHMIC VOLTAGE LOSS
```

```
R_ionic1=L1/(sigma*A);V_ohm1=I.*(R_elec+R_ionic1);

R_ionic2=L2/(sigma*A);V_ohm2=I.*(R_elec+R_ionic2);

R_ionic3=L3/(sigma*A);V_ohm3=I.*(R_elec+R_ionic3);

R_ionic4=L4/(sigma*A);V_ohm4=I.*(R_elec+R_ionic4);

R_ionic5=L5/(sigma*A);V_ohm5=I.*(R_elec+R_ionic5);

% PLOT THE OHMIC LOSS AS A FUNCTION OF ELECTROLYTE THICKNESS

figure1=figure('Color',[1 1 1]);

hdlp=plot(i,V_ohm1,i,V_ohm2,i,V_ohm3,i,V_ohm4,i,V_ohm5);

title('Ohmic Loss as a function of Electrolyte Thickness','FontSize',14,'FontWeight','Bold')

xlabel('Current Density (A/cm^2)','FontSize',12,'FontWeight','Bold');

ylabel('Ohmic Loss(V)','FontSize',12,'FontWeight','Bold');

legend('L=0.0025','L=0.0050','L=0.0075','L=0.01','L=0.015')

set(hdlp,'LineWidth',1.5);

grid on;
```

```
V_ohm =     0.3850
```

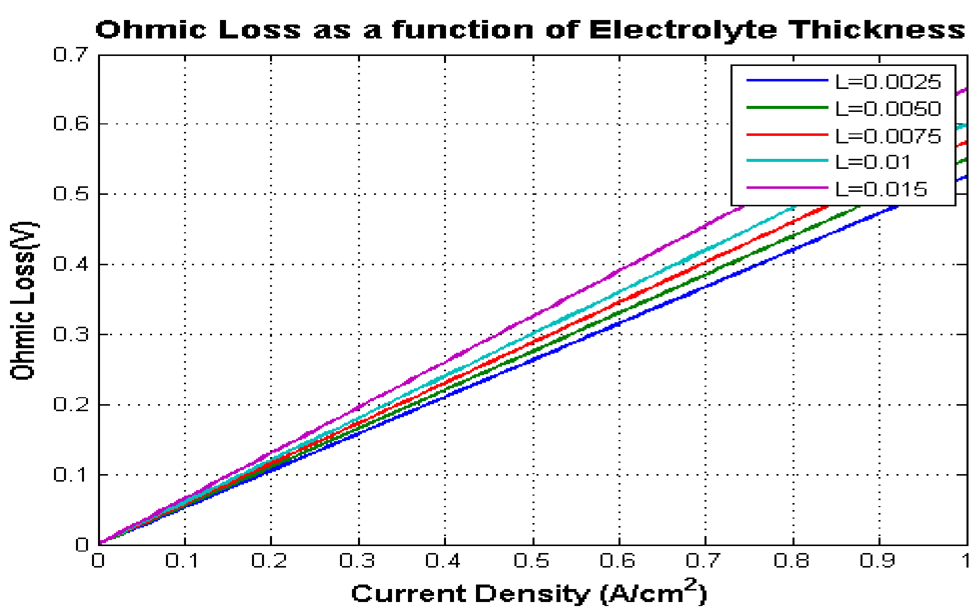

Figure 4: Ohmic loss vs current density

8.4.2: Program to calculate the ohmic losses as a function of fuel cell area.

```
% CALCULATING THE OHMIC VOLTAGE LOSS WITH DIFFERENT FUEL CELL

% INPUTS

i=0.7; % CURRENT DENSITY (A/cm^2)

R1=0.05; % RESISTANCE (ohms)

A=1:100;

ASR=R1*A;

% CALCULATE THE TOTAL CURRENT

I=i*A;

% CALCULATE THE OHMIC VOLTAGE LOSS

V_ohm=I.*R1;

% PLOT OF THE OHMIC LOSSES AS A FUNCTION OF FUEL CELL AREA

figure1=figure('Color',[1 1 1]);

hdlp=plot(A,V_ohm);

title('Ohmic Loss as a function of Fuel Cell

area','FontSize',14,'FontWeight','Bold')

xlabel('Fuel Cell Area (cm^2)','FontSize',12,'FontWeight','Bold');

ylabel('Ohmic Loss (V)','FontSize',12,'FontWeight','Bold');

set(hdlp,'LineWidth',1.5);

grid on;
```

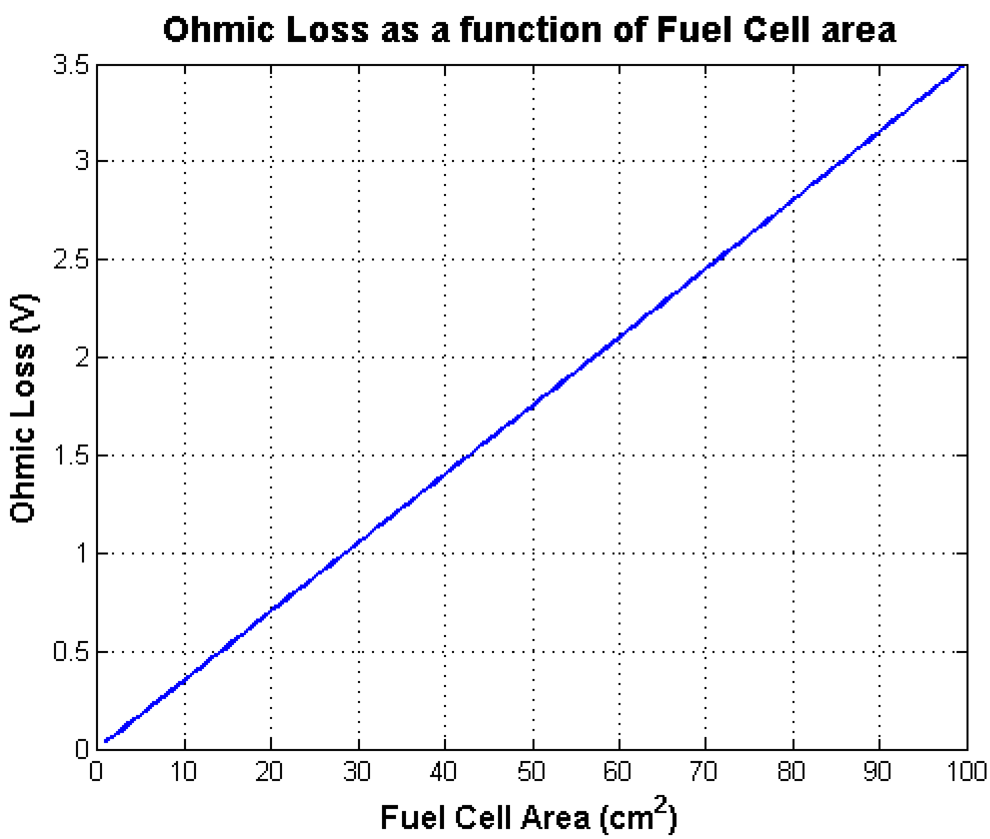

Figure 5: Ohmic loss Vs Fuel cell area

8.4.3: MATLAB code to calculating ohmic voltage loss due to the membrane

```
clc;
% CALCULATING OHMIC VOLTAGE LOSS DUE TO THE MEMBRANE
% INPUTS
global T; global F; global C; global alpha; global den_dry; global Sigma_a;
global z; global A; global n; global i; global Mn; global D;
Tc=20:10:80; % TEMPERATURE IN CELSIUS
T=Tc+273.15; % TEMPERATURE IN KELVIN
z=0.005; % MEMBRANE THICKNESS (cm)
aw_a=0.8; % WATER ACTIVITY AT THE ANODE
aw_c=1;  % WATER ACTIVITY AT THE CATHODE
```

```
n=2.5; % ELECTRO-OSMOTIC DRAG COEFFICIENT

i=0.8; % CURRENT DENSITY (A/cm^2)

Mn=1; % NAFION EQUIVALENT WEIGHT(kg/mol)

F=96487; % FARADAY'S CONSTANT

den_dry=0.00197; % MEMBRANE DRY DENSITY(kg/cm^3)

C=2.3; % CONSTANT DEPENDENT UPON BOUNDARY CONDITIONS

alpha=1.12; % RATIO OF WATER FLUX TO HYDROGEN FLUX

% CONVERT THE WATER ACTIVITY ON THE NAFION SURFACES TO WATER CONTENTS

lambda_anode=0.043+(17.81*(aw_a))-(39.85*(aw_a^2))+(36*(aw_a^3));

lambda_cathode=0.043+(17.81*(aw_c))-(39.85*(aw_c^2))+(36*(aw_c^3));

% CALCULATE THE WATER DIFFUSIVITY

D=(10.^-6).*exp(2416.*(1./303-1./T)).*(2.563-(0.33.*10)+(0.0264.*10.^2)-
(0.000671.*10.^3));

delta_lambda=((11.*alpha)./n)+C.*exp(((i.*Mn.*n)./(22.*F.*den_dry.*D)).*z);

Sigma_a=exp(1268.*((1./303)-(1./T))).*(0.005139.*delta_lambda-0.00326);%S/m

Sigma_c=exp(1268.*((1./303)-(1./T))).*(0.005139.*delta_lambda-0.00326);%S/m

Re_a=quad('thick',0,0.0050)

V_ohm=i*Re_a

% PLOT

z=0:0.002:0.0125;

delta_lambda=((11.*alpha)./n)+C.*exp(((i.*Mn.*n)./(22.*F.*den_dry.*D)).*z);

Sigma=(1268.*((1./303)-(1./T))).*(0.005139.*delta_lambda-0.00326);% S/m

% PLOT THE MEMBRANE THICKNESS AND WATER CONTENT

figure1=figure('Color',[1 1 1]);

hdlp=plot(z,delta_lambda);

title('Membrane Thickness and Water
content','FontSize',14,'FontWeight','Bold')

xlabel('Membrane Thickness (cm)','Fontsize',12,'FontWeight','Bold');

ylabel('Water Content (H2O/SO3)','Fontsize',12,'FontWeight','Bold');
```

```
set(hdlp,'LineWidth',1.5);

grid on;

% PLOT THE MEMBRANE THICKNESS AND LOCAL CONDUCTIVITY

figure2=figure('Color',[1 1 1]);

hdlp=plot(z,Sigma);

title('Membrane Thickness And Local
Conductivity','FontSize',14,'FontWeight','Bold')

xlabel('Membrane Thickness (cm)','FontSize',12,'FontWeight','Bold');

ylabel('Local Conductivity (S/cm)','FontSize',12,'FontWeight','Bold');

set(hdlp,'LineWidth',1.5);

grid on;
```

```
Re_a =     0.0734            V_ohm =     0.0587
```

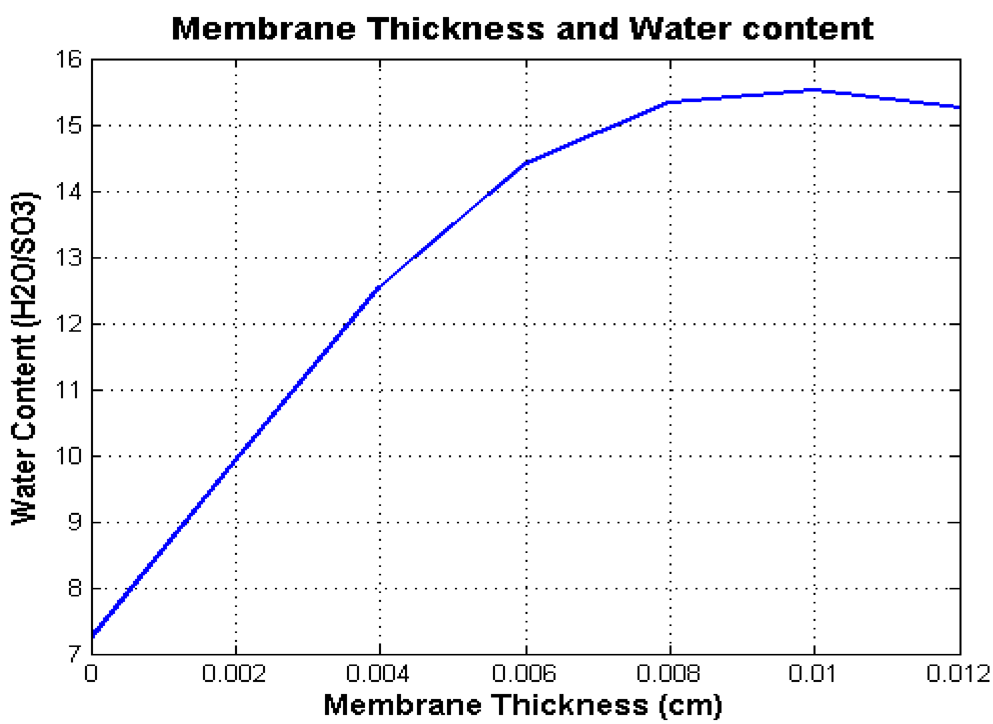

Figure 6: Water content Vs membrane thickness

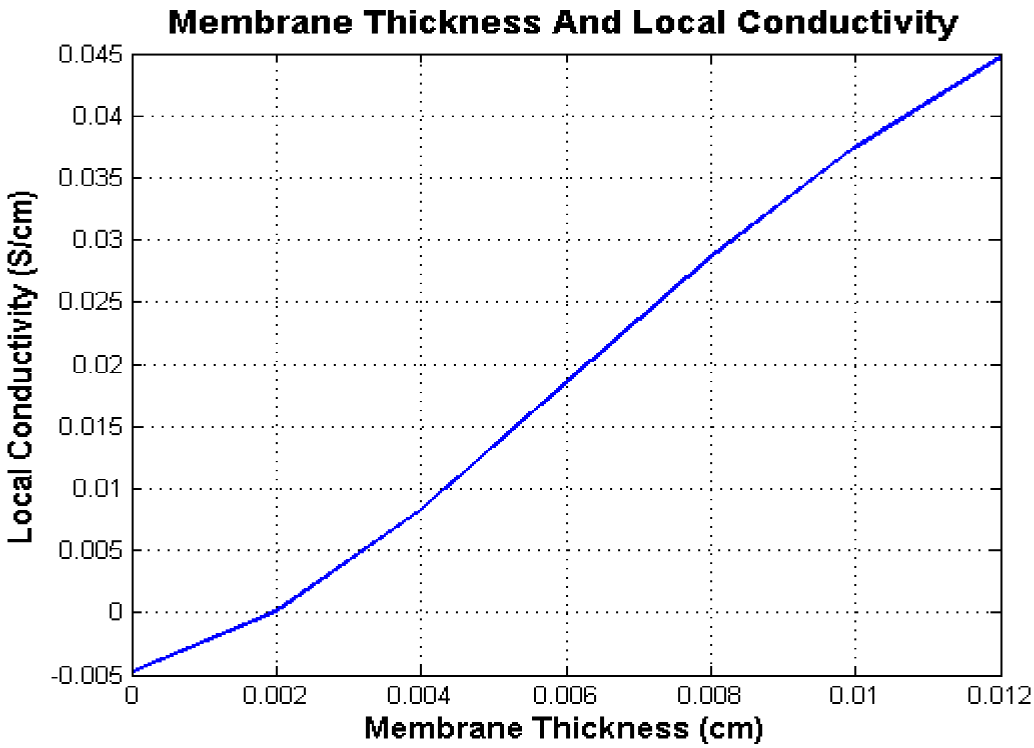

Figure 7: Local conductivity Vs membrane thickness

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CONCLUSION AND SCOPE FOR FUTURE WORK

India has enormous potential for development in solar power due to large number of sunny days per year and a large mainland area. Solar thermal energy is an easy and economical source of electrical power. For large power requirement, solar central receiver is suitable. India ranks 4^{th} in the world in terms of existing capacity and 3^{rd} in terms of new wind power added. Newton- Raphson method if applied will give convergence in less iteration compared to G-S method.

As I have made a feasibility study of setting up a Photovoltaic plant at Rourkela, A local contractor can be hired to build a pole kit with PV modules mounted above the lamp and the battery enclosure mounted to the pole near ground level. The modules are prewired and assembled in an Aluminum frame that is attached to the pole at the proper tilt angle. The array conductors can be run down the inside of the metal pole to the control box mounted to the pole behind the battery enclosure. The battery box can be shaded with a metal overhang to maintain ambient temperature. To protect the poles from lightning, lightning rods can be attached.

Solar photovoltaic power can be used at remote villages to provide light during night-time. This will promote literacy among village children and encourage men &women to take up handicraft work as an option to earn extra money. A survey in this regard can be made. Also, solar electricity can be used to drive motor to pump water during day. This will reduce peak load on grid and ensure lesser power cuts.

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Appendix

Solar radiation data for New Delhi and Bombay

TABLE 1

Month	Mean Total* kWh/(m^2.day)	
	New Delhi (28^0N)	Mumbai (19^0N)
January	3.99	5.0
February	5.00	5.76
March	6.14	6.45
April	6.93	6.99
May	7.28	7.26
June	6.54	5.17
July	5.33	4.06
August	5.05	3.98
September	5.60	4.88
October	5.35	5.44
November	4.52	5.07
December	3.84	4.79

*Global radiation = Beam radiation + Diffuse radiation.

Solar radiation & data measurement laboratories in India

TABLE 2

Sl. No.	Location
1	Ahmedabad, Gujarat
2	Bhavnagar, Gujarat
3	Calcutta, W.B.
4	Panaji, Goa
5	New Delhi
6	Nagpur, Maharashtra
7	Madras, T.N.
8	Mangalore
9	Kodaikanal, T.N.
10	Port Blair
11	Pune, Maharashtra
12	Shillong, Assam
13	Trivandrum, Kerala
14	Jodhpur, Rajasthan
15	Vishakapatnam, A.P.

Tabulation of values of ‘a’ and ‘b’ at different locations in India

TABLE 3

City	a	b
Ahmedabad	0.28	0.48
Bangalore	0.18	0.64
Bhavnagar	0.28	0.47
Bhopal	0.27	0.50
Calcutta	0.28	0.42
Goa	0.30	0.48
Jodhpur	0.33	0.46
Kodaikanal	0.32	0.55
Madras	0.30	0.44
Mangalore	0.27	0.43
Nagpur	0.27	0.50
New Delhi	0.25	0.57
Pune	0.31	0.43
Roorkee	0.25	0.56
Shillong	0.22	0.57
Srinagar	0.35	0.40
Trivandrum	0.37	0.39
Vishakapatnam	0.28	0.47

Characteristics and features of solar thermal collector systems

TABLE 4

Sl. No.	Type of collector	Temperature of working fluid	Principle of collection	Cost and simplicity of sun-tracking
1.1	Simple Flat Plate	-Low temperatures around 150^0C - C.R.#=1	1. Radiation received by the surface without focusing 2. Surface gets heated.	Usually not provided as too costly.
1.2	Modified Flat Plate	Temp = 200^0C C.R. =1.2	1. Both beam and diffuse component are collected. 2. Distributed collectors.	Simple, low cost
2	Parabolic trough type collector with line focus	Moderate temperatures around 300^0C C.R.= 2 to 100	1. Parabolic trough shaped mirrors reflect the beam radiation on axial pipe. 2. Line focus on central axis. 3. Pipe on axis absorbs energy and transfers to working fluid 4. Only beam radiation collected 5. Distributed collector.	Tracking in one plane for daily movement of the sun, Adjustment of orientation for seasonal variation, Moderate cost
3	Paraboloidal dish with point focus distributed collector/ Fresnel lens point focus distributed collector	Higher temperature around 1000^0C or higher C.R.=200 to 10000	1. Paraboloid dish shaped reflectors focus the reflected high rays on the center of paraboloid 2. Point focus 3. Reservoir containing heat transport fluid located at focal point 4. Distributed collector system 5. Only beam radiation is collected.	Requires tracking in two planes for daily and seasonal orientation High cost
4	Central receiver and central focus with heliostats on ground level	High temperature 1200^0C C.R. = 200 to 1000	1. Several nearly flat mirrors on ground reflect the beam radiation on a central receiver/ furnace on a tall tower. 2. Heat transfer fluid in central receiver absorbs energy. 3. Only beam component of sunlight is reflected. Diffuse component is not reflected.	Mirrors must track the sun individually in two planes, Most complex, higher cost

#C.R. = Collector Ratio = $\dfrac{\frac{kW}{m^2} in\ solar\ radiation\ on\ surface}{\frac{kW}{m^2}\ on\ surface\ of\ focus\ of\ collector}$

Heat transfer fluid

Following 5 types of fluids are commonly used for heat transfer:

1. Water-steam
2. Liquid metals e.g. Sodium
3. Molten salts e.g. Nitrate salt mixtures.
4. Gases such as Air, Nitrogen, Helium.
5. Heat transfer oils.

TABLE 5 *Characteristics of Heat Transfer Fluids*

Sl.No.	System	Remarks
1	Water-Steam	1. Low development cost, well established technology. 2. Used as heat transfer fluid and working fluid. 3. Steam temperature 540 to 600^{o}C. 4. Steam pressures 70 to 140 bar. 5. Used for distributed receiver system and central receiver system. 6. Less efficient heat transfer fluid.
2	Liquid metals	1. Sodium (Na) system under development. 2. High heat transfer coefficient. 3. More compact receiver. 4. Sodium freezes at 98^{o}C requires auxiliary heating during shut down. 5. Cover gas such as Argon used to prevent oxidation. 6. Operating temperature 540^{o}C. 7. Boiling point 883^{o}C. 8. High pressurization not required.
3	Molten salts	1. Nitrate salt mixtures under consideration. 2. High operating temperature. 3. Freezing point 140 to 220^{o}C and requires auxiliary heating.
4	Gases	1. High temperatures (Above 840^{o}C) 2. Pressurization necessary to increase mass-flow rate 3. Air, Nitrogen and Helium are considered. 4. Used as heat transfer fluid or working fluids.
5	Heat transfer oil	1. Low corrosion or pipes and receiver. 2. Decomposed at higher temperature. 3. Temperature range: 7 to 300^{o}C 4. Used as heat transfer fluid. 5. High mass flow rate and heat transfer coefficient.

Reference data of a Solar Central Receiver power plant

TABLE 6

Nominal Rating	100 MWe
Number of Modules	
Base load modules	3
Intermediate load modules (Storage capacity – 6 hours)	2
Peaking load module (Storage capacity – 3 hours)	1
Hybrid module (Solar plus battery storage for ½ hours)	1
Features of Each module	
Central tower height	250 m
Reflector surface area per module	0.5 km^2
Area of utilization	38%
Total land area per module	1.3 km^2
Number of collectors per module	15400
Surface area of each collector	32.5 m^2
Data for total plant	
Nominal power rating	100 MWe
Number of modules	7
Total land area	9 km^2
Total number of collectors	107,800

World's major solar central receiver power plants

TABLE 7

Place	Year	Particulars
Dagget, California, USA (Solar One Plant)	1982	• 10 MWe peak • Water steam as heat transport • Experimental, pilot plant
Almeria, Spain	1981	• 500 kWe peak • Molten sodium as heat transport fluid • In parallel with 500kWe peak distributed receiver line for plant • 93 heliostats 40 m^2 each for 500 kWe plant, 43 m tower
Almeria, Spain	1982	• 3 MWe • Water steam as heat transport medium • 300 Heliostats, 40 m^2 each • Temperature of steam 525^{0}C
Adrano Sicily, (Eurelios To plant)	1981	• 1 MWe • Tower 55 m • Temp. 510^{0}C • Storage fluid = Hytec.
Thermis, France		• 2 MWe • 200 heliostats 52m^2 each • Heat transport fluid Hytec.

Intermediate Compounds

Any of types of Silicon (Homo-crystalline, poly-crystalline, Amorphous) are treated with any of the following intermediate compounds to form N-P junctions:

1. Cadmium-Sulphide
2. Gallium-Arsenide
3. Zinc-Sulphide
4. Gallium-Antimonide
5. Cadmium-Territide
6. Indium-Phosphate
7. Cadmium-Selenide

Efficiency of a solar cell

- Efficiency = $\frac{Incident\ radiation\ (W)}{Power\ Delivered\ (W)}$
- A PV cell must be operated at knee point with maximum possible incident light for obtaining maximum power and therefore high efficiency.
- Maximum efficiency achieved in laboratories is 15-20 %. Maximum theoretical possible efficiency is 25%.

TABLE 8

Cell Efficiency	**1980s**
With amorphous silicon	5%
With polycrystalline silicon	7%
With single crystalline silicon	12%

#Efficiency of solar PV module is lesser than cell efficiency due to lesser area coverage factor (Solar cell area/ module area).

Limiting factors to cell efficiency, η

1. *Top surface contact obstruction (loss ~3%)*

The electric current leaves the top surface by a web of metal contacts arranged to reduce series resistance losses in the surface. These contacts have a finite area and so they cover part of the active surface.

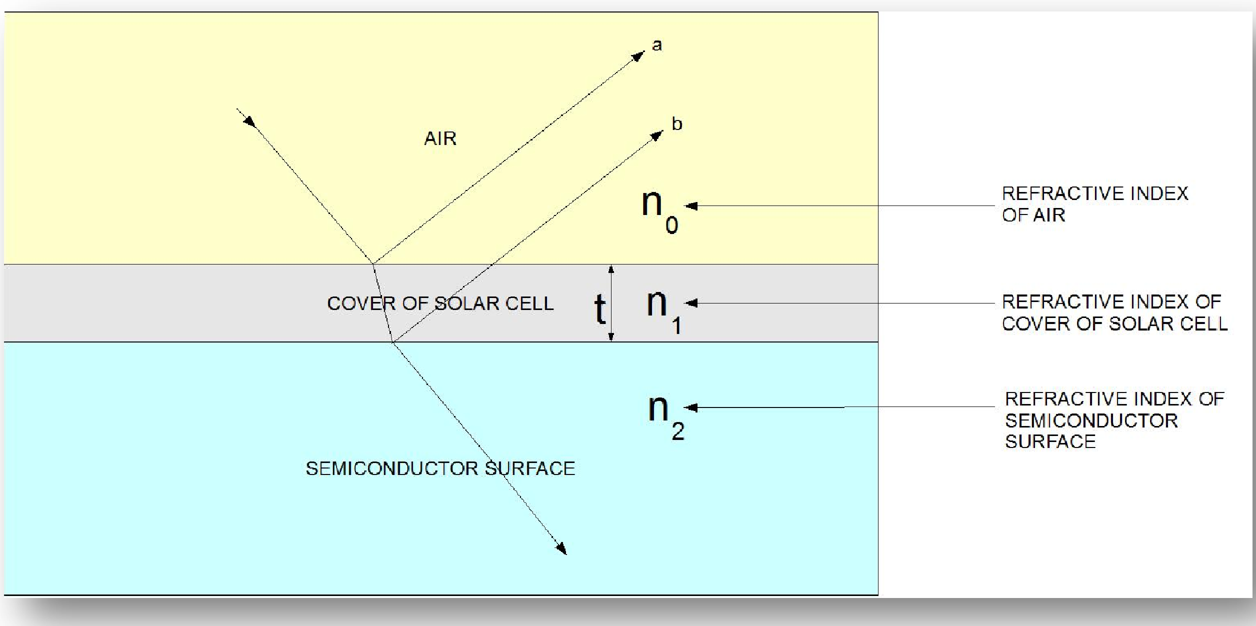
2. *Reflection at top surface (loss ~1%)*

The reflectance from semiconductors is as high as ~40% of incident solar radiation. They are chemically treated or a thin film is deposited to reduce it to 3% or less.

For dielectrically insulating materials, the reflectance between two media is $\rho_{ref} = \frac{(n_0-n_1)^2}{(n_0+n_1)^2}$.

The refractive index of semiconductors is 3.5 in magnitude.

For air, n_0=1. Therefore the reflectance in air varies from ρ_{ref}(1.1eV)=34% to ρ_{ref}(5eV)=54%. A thin film (of thickness t) reduces reflection losses.



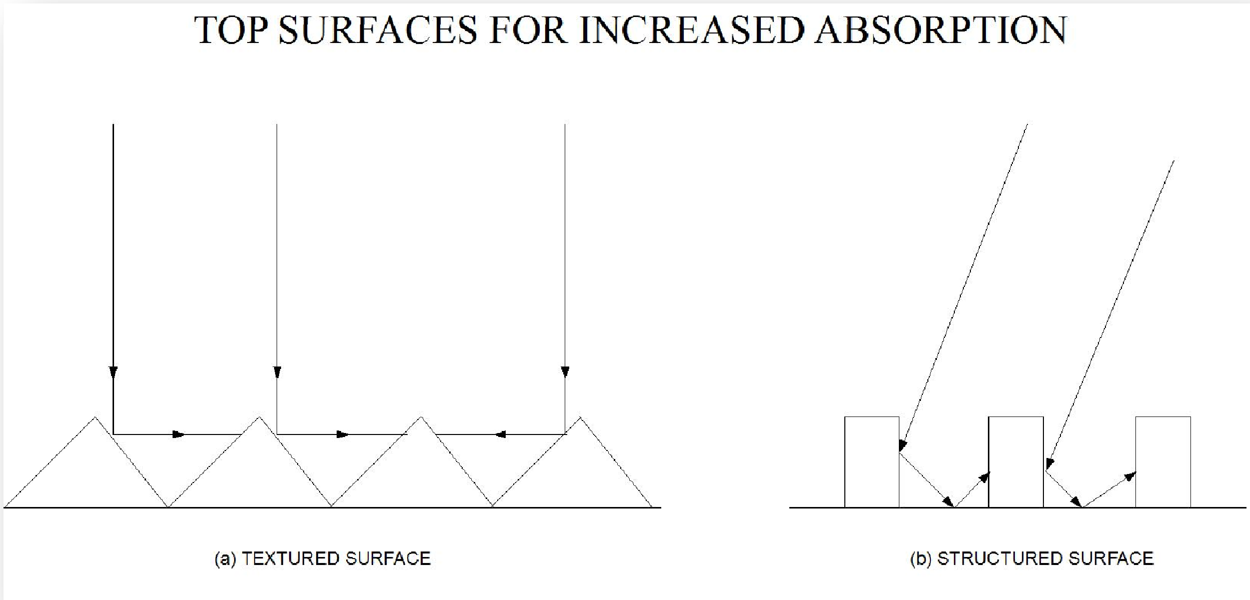
Rays 'a' and 'b' shown in figure are of equal intensity and differ in phase by π radians (path difference λ/2).

Conditions:

- $n_1=\sqrt{(n_0 n_2)}$
- $t=\lambda/(4n_1)$

For Si (if n_1=1.9, thickness t=0.08 μm) the broad band reflectance is reduced to ~6%.

Reflection losses are reduced by top layer configuration that reflects the beam for a second opportunity of absorption. These surfaces can be produced by chemical etching of Si.



3. *Photon energy less than band gap (loss ~23%)*

Photons of quantum energy $h\nu<E_g$ cannot contribute to photovoltaic current generation. For Si ($E_g\approx1.1eV$) the inactive wavelengths have $\lambda\geq1.1\mu m$ and include 23% of AM1 insolation. If this energy is absorbed it causes heating with a temperature rise that lowers power production. These photons can be theoretically removed by filters. More efficient strategy is to use heat in a combined heat and power system.

4. *Excess photon energy (loss ~33%)*

The excess energy of active photons ($h\nu$-E_g) also appears as heat.

5. *Quantum efficiency (loss ~0.4%)*

Quantum efficiency-the fraction of incident absorbed active photons producing electron-hole pairs-is usually very high. Design of solar cell becomes profitable only if it can catch 95% of incident energy.

6. *Collection efficiency*

Collection efficiency is the proportion of radiation generated electron-hole pairs that produce current in the external circuit. It directly affects the overall efficiency of cell.

7. Voltage factor F_V (loss ~4%)

Each absorbed photon produces electron-hole pairs with a constant potential difference but only a portion of it is available for EMF in the external circuit.

The voltage factor is $F_V = \frac{eV_B}{E_g}$.

In Si, F_V ranges from ~0.6 (0.01Ωm material) to ~0.5 (0.1Ω m material).

This result in production of $V_B \approx$ 0.66 to 0.55 V.

When producing current under load, heat is produced due to movement of carriers.

8. Curve factor F_C (loss ~4%)

I-V characteristic of a solar cell depends on p-n junction characteristics and therefore, peak power P_m is less than the product of $I_{SC}V_{OC}$ as

$$I = I_0 . \exp^{\left[\frac{eV}{(AkT)} - 1\right]} - I_L$$

Curve factor is given as $F_C = P_{max}/I_{SC}V_{OC}$ and is maximum 0.88 for Si.

9. Additional curve factor 'A' (loss ~5%)

The factor 'A' results in cell due to increased recombination. This tends to change V_{OC} and I_{SC} as a result maximum power output is when A=1.

10. Series resistance (loss ~0.3%)

The solar cell current passes through a circuit having non-uniform resistance. The exposed surface is made maximum to absorb large solar insolation but the contacts are made thin for low contact loss. The power loss is equivalent of a series resistor present in a circuit wasting energy. Surface layouts are changed to reduce the series resistance to 0.1Ω in a cell of resistance 20Ω.

11. Shunt resistance (loss ~0.1%)

Shunt resistance appear in circuit due to imperfections on structure of edge of cell. However this results in negligible loss. For single crystal Si cell, shunt resistance is considered infinite. But this is not true in polycrystalline cells.